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Airborne Severe Storm Surveillance

Volume I
Summary and Recommendations

J. W. Meyer,
Editor

17 December 1970

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

AIRBORNE SEVERE STORM SURVEILLANCE
VOLUME I. SUMMARY AND RECOMMENDATIONS

Report to the
Advanced Research Projects Agency
of a Summer Study
3 through 28 August 1970

J. W. MEYER, Editor

Division 4

TECHNICAL NOTE 1970-43

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LEXINGTON MASSACHUSETTS

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ABSTRACT

The report of the Summer Study is presented in two volumes. Volume I, Summary and Recommendations, includes background material, the principal findings supported in most instances by brief discussion, and recommendations, in the form of brief statements, made as a result of the findings. Volume II, Reports of the Working Panels, contains material prepared by the Panels, which represents more detailed discussions in support of both the findings and recommendations.

Airborne reconnaissance required to improve the forecasting and warning of severe tropical storms (hurricanes and typhoons), and to support efforts to achieve effective storm modification, is emphasized. Other methods of getting the necessary information and data are considered, and where appropriate, are recommended as part of the total system. Also discussed is the application of advanced ground-based and aerospace techniques to other kinds of violent weather, e.g., East Coast winter storms and violent thunderstorms producing tornadoes. While it is recognized that a degree of specialization is required for the most effective application of technology to problems, the severe storm surveillance system as a whole is viewed as an important national resource that can be used effectively in our defense against a variety of environmental hazards.

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

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APPENDICES

I. INTRODUCTION

A. Objective

The principal objective of the Study Group was to attempt definition of the airborne component of an integrated surveillance system consisting of sensory, data-processing, navigation, and communications equipment capable of detecting, tracking, and measuring for analysis hurricanes/typhoons during genesis and development, and during periods of active weather modification. As a secondary objective, we would delineate those airborne system features that could contribute to our understanding and forecasting of tornadoes, convective thunderstorms, and winter coastal cyclones.

II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Contemporary operations are carried out by dedicated people doing incredibly well with limited available technical resources.
2. There is a substantial measure of existing technology developed for other purposes that could be profitably applied.
3. The application of new technology can be begun immediately in the existing system, and there is the possibility of orderly growth to an advanced severe storm surveillance system.
4. There are a number of new techniques of meteorological measurement and new sensor concepts that need further investigation of their potential for this application.
5. The potential saving of life by credible warning, and the saving of the cost of preparations in over-warned areas, are enough to warrant an increased investment in an improved forecasting and warning system.
6. The potential saving of life and property by effective storm modification is so great that increased research and development toward this goal is also imperative.

B. Recommendations — General:

We recommend:

1. Improvement of our current systems to enable us to:
   a. Reduce the distance between actual and 24-hour forecast hurricane landfall to less than 50 miles;
   b. Improve the forecast of maximum winds, rainfall, and flood-producing storm surges.
2. Augmentation of research and development in hurricane modification with the goal of diminishing the maximum winds of threatening hurricanes by 25%.

C. Recommendations — Specific:

1. Conduct a systems study by a full-time, permanent organization as a sequel to this Summer Study to relate the required observations with the several suggested alternative ways of making the measurements, the kind of reconnaissance we would have in the absence of hurricane warning needs, the costs of developing and

supplying the equipment indicated for the required measurements, and the costs of implementing the aggregate systems so that priorities can be established.

2. Move immediately to improve the quality of meteorological data taken by airborne systems by improving calibration methods and facilities and increasing commonality of measurements.
3. Provide direct and real-time communications between reconnaissance elements and the center responsible for forecast and warning.
4. Improve navigation systems in operational reconnaissance aircraft.
5. Establish FAA air traffic control priority for storm reconnaissance aircraft.
6. Exploit the potential of radar to make quantitative measurements of winds, up- and down-drafts, and intensity of rainfall on both airborne and ground radars.
7. Seek allocation of a channel in the FM broadcast band for Weather Bureau broadcasts of warnings and information of the kind now broadcast on their VHF broadcast service.
8. Implement an advanced air-transportable ground station for deployment to areas threatened by severe storms.
9. Improve utilization of satellite measurements by improving sensors and by evolving forecasting techniques that make better use of the kind of measurements possible from a satellite.
10. Develop a high-altitude reconnaissance aircraft prototype with the objective of getting the necessary measurements on a storm without aircraft penetration.
11. Investigate radiometric methods of making needed storm measurements.
12. Study the mass psychology and human factors problems involved in alerting and warning of the public on the occasion of threatening severe storms.

III. BACKGROUND INFORMATION

A. Camille

In the aftermath of Hurricane Camille(Fig. 1), which in 1969 struck the Gulf Coast with devastating force, President Nixon asked Vice President Agnew to conduct a survey of our hurricane reconnaissance forecast and warning system. In the course of this survey, the Vice President was informed that the aerial weather reconnaissance support was not all it should be. The President in an August meeting of the Environmental Quality Council asked the Secretary of Commerce to ensure that appropriate aircraft with the best available equipment be used on all future occurrences.

B. Camille Survey Team

A survey team was formed to look into the circumstances surrounding the reconnaissance and warning on Camille. This team described operations, forecasts, and warnings connected with Camille in a report to the Administrator, Environmental Science Services Administration (ESSA), entitled "Hurricane Camille," dated September 1969. (See Fig. 2.)

C. Camille Reconnaissance

A second survey convened by the Federal Coordinator for Meteorological Services and Supporting Research concentrated on aerial reconnaissance of Camille. A "Report on Hurricane Weather Recommaissance," (FCM 69-1, dated September 26, 1969), pointed to four primary factors contributing to "less than optimum" reconnaissance. Briefly stated, these factors were: 1) Navy aircraft are unable at low levels ($\leq$ 1500 ft) to penetrate to the eye of severe hurricanes; 2) Air Force weather radars operating at 3-cm wavelengths perform poorly in heavy rain; 3) Post-flight liaison between the National Hurricane Center (NHC) and flight crews was not good enough; and 4) The 1969 National Hurricane Operations Plan did not reflect all the data needed or desired by the forecasters.

D. Seek Storm

A special effort to improve radars used by the Air Force for storm reconnaissance, a program called "Seek Storm" was launched, which had as its objective the development of an improved radar system to be installed on the WC-130 or the WC-135 weather reconnaissance aircraft.

E. Lincoln Laboratory Study

Lincoln Laboratory was asked by the Electronic Systems Division, Air Force Systems Command, to conduct a short study of the requirements for a hurricane reconnaissance aircraft radar system. The results and recommendations of this study are contained in Lincoln Laboratory Technical Note 1970-5, "Report on a Weather Radar Study for Aerospace Instrumentation Program Office (ESSI), Electronic Systems Division," dated 5 February 1970. In this report, recommendations were made in the context of what could be done in three time periods: by the 1970 hurricane season; by mid-1971; and by the time of the implementation of a program designed to improve instrumentation in an advanced Airborne Weather Reconnaissance System (AWRS), Program 5222, in mid-1972.

The Study indicated that entirely satisfactory surveillance radar performance for hurricane reconnaissance could not be achieved without a large antenna, which in turn would involve a major modification to the aircraft and perhaps affect adversely its air-worthiness in severe storms.

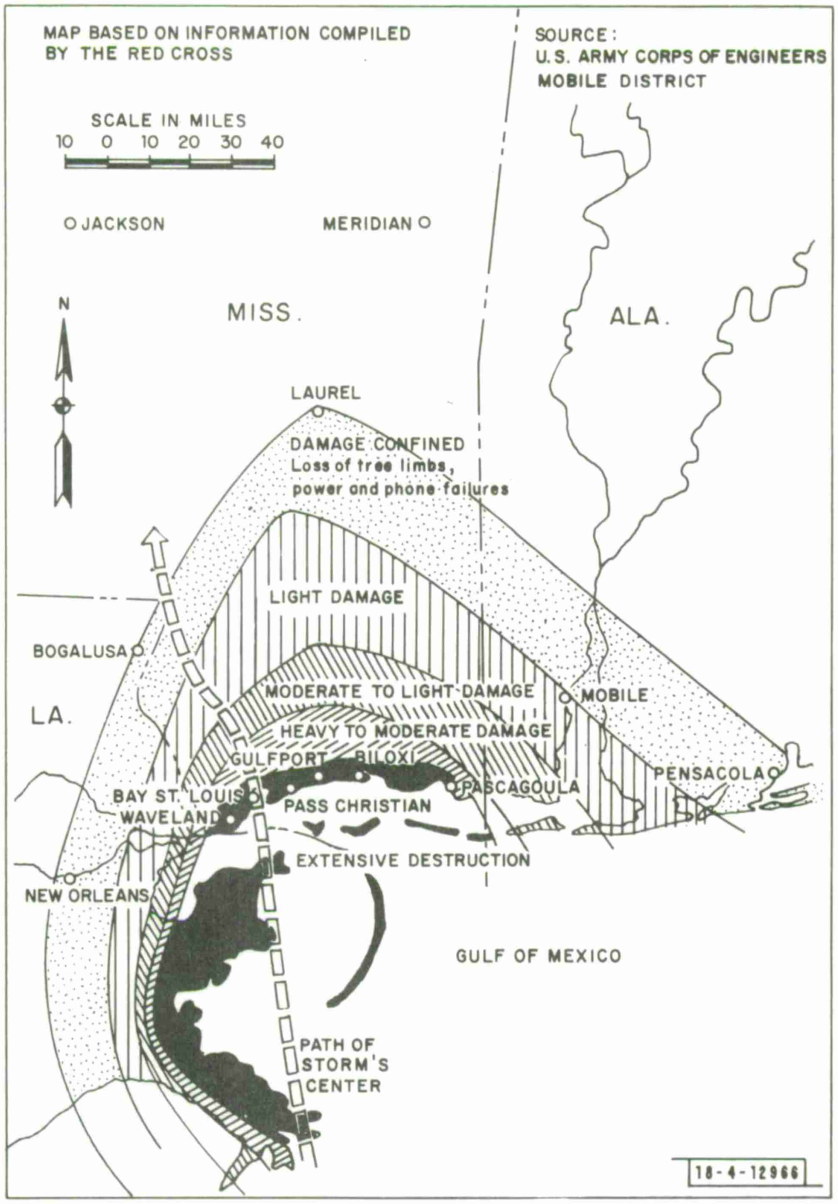

Fig. 1. Hurricane Camille. Map of damage and destruction levels. The pattern of damage relative to the storm's path shows the effect of higher wind speeds on the right side of the storm where the winds are a result of the combination of cyclonic circulation plus 15-20 knots from the forward motion of the storm.

From: URS Research Company, San Mateo, California. Report URS-792-2, March 1970, AD 708568, "The Effects of Hurricane Camille on Industry, Public Utilities, etc." by Robert H. Black.

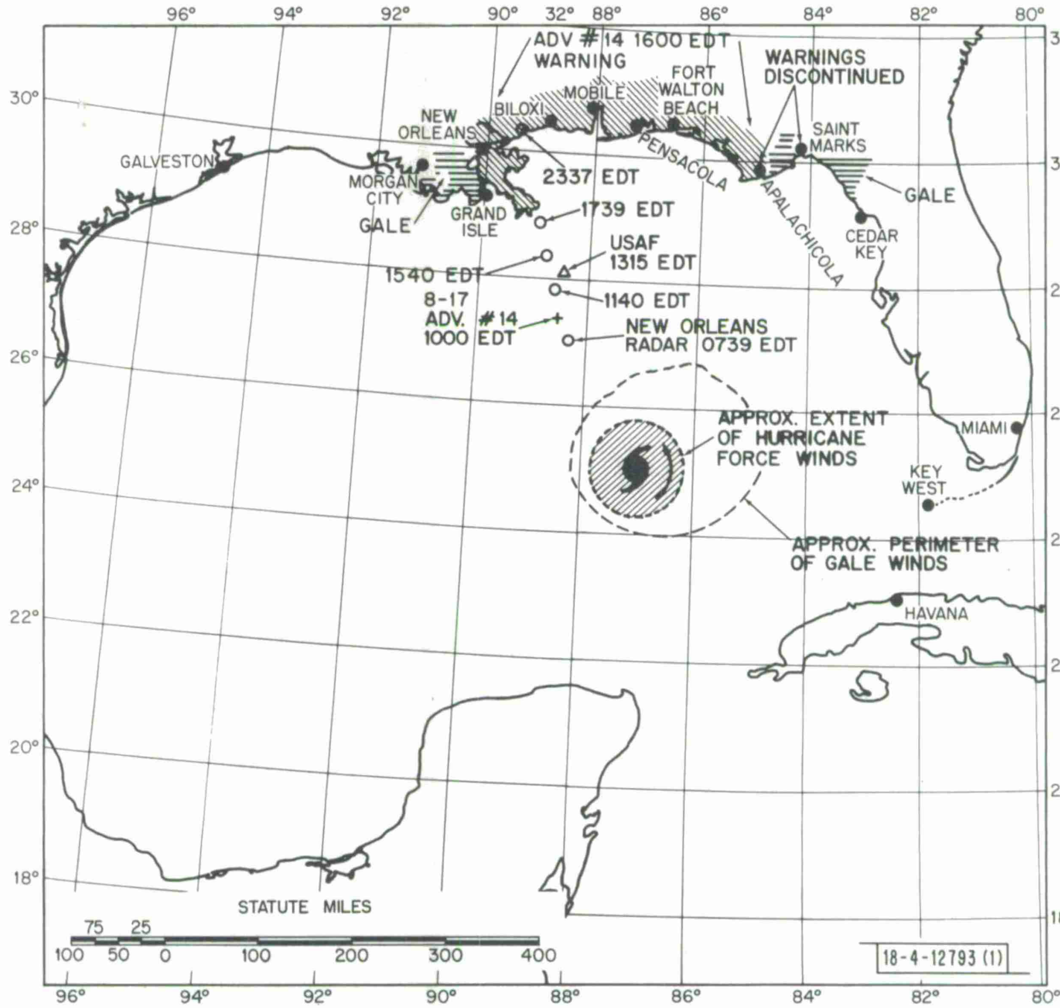

Fig. 2. Reconnaissance fixes, warnings and bulletins during the final hours of Camille's approach to Bay St. Louis, Mississippi and vicinity. Note the position announced in Advisory #14 at 1000 EDT, 17 August 1970, the area in which hurricane warnings were effective in that advisory and those coastal areas alerted for gale force winds. Camille's center was at Bay St. Louis at 2337 EDT.

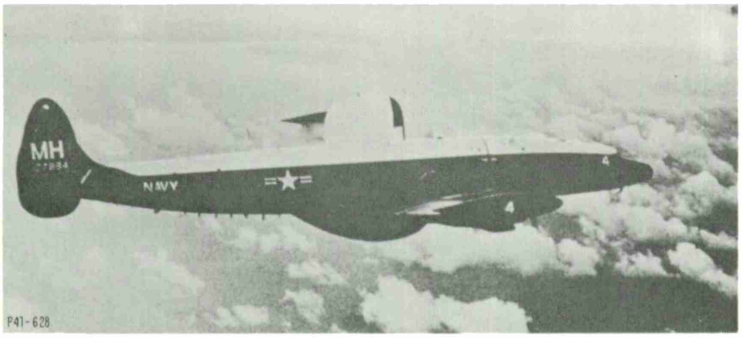

Fig. 3. Navy WC-121. This aircraft (Constellation) has the best radar (APS-20) in current use for PPI display of hurricanes as viewed to ranges of over 200 n.mi. from the storm center. When used at low altitudes, sea clutter interference is minimized. A powerful X-band radar (APS-45) with good vertical resolution is used to get RHI information.

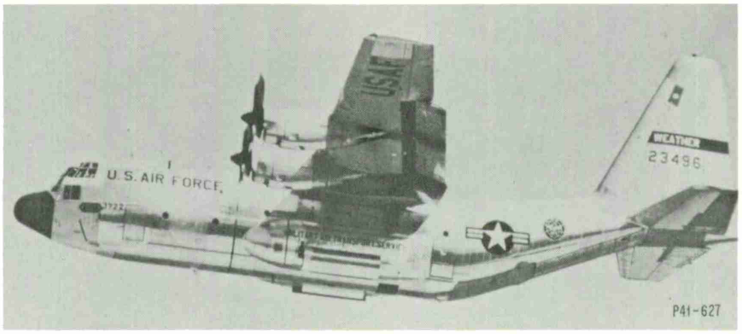

Fig. 4. Air Force WC-130. This turboprop aircraft (Hercules) is the most modern of the hurricane reconnaissance fleet and has successfully penetrated the most severe storms. It is equipped with an X-band weather avoidance radar (APN-59B).

Fig. 5. Research Flight Facility DC-6. This aircraft is equipped with an Omega navigation system and advanced meteorological instrumentation for flight level measurements. It is equipped with C-, S-, and X-band radars, all with relatively small antennas.

Even in the longest available time, it was clear that built-in constraints permitted little real innovation in hurricane reconnaissance as a whole. Yet there was a continuing need for providing forecasters with what today is a principal datum, the lowest sea-level pressure in the eye of the hurricane. With today's reconnaissance aircraft (Figs. 3, 4, 5), this makes necessary the penetration of rain bands and eye-wall clouds containing heavy rainfall and substantial turbulence.

As an aid to pilotage in these conditions, the installation of a C-band radar in the WC-130 without changing the radome conformation was recommended. While it was recognized that the longer operating wavelength with no increase in antenna size would mean a loss of angular resolution, holding the line on air-frame modifications would permit installation in a few months' time. It was believed more important to pilotage in penetrations to be able to see through heavier rainfall than to have greater angular resolution. This was clearly an interim and ad hoc solution and by no means represented what we believed could and should be done in airborne radar surveillance of hurricanes.

F. The 1970 Summer Study — A More General Review

It was clear that real innovation would require participation by all parties to the severe storm forecasting and warning task, plus representatives of our substantial instrumentation technology in a study of the appropriate conformation of what might be called an airborne severe storm surveillance system. This participation was realized in the present Study.

Weather data use for purposes of forecasting and warning is extremely evanescent. The data obtained from storm reconnaissance has to be calibrated, processed, communicated, and displayed in a time short enough to be of utility to the users, those responsible for forecasting and issuing warnings to the public. Such data, however, if properly recorded and calibrated, can be invaluable to research workers long after the fact. We have much to learn about processes occurring in severe storms. Operational weather reconnaissance missions can and should provide needed research data as a secondary objective.

We endeavored to look at the problem of severe storm reconnaissance with a view to the future beyond the above time constraints, to approach the problem with as little preconception as possible, to define the necessary measurements, and to suggest the best way of making them. Even with this objective, we did not feel we could ignore, nor did we, the important contribution that might be made to improve the current severe storm warning system. An airborne system or instrumentation that we might suggest for eventual operational use would, of course, have to fit into the then contemporary operational scene. In the case of research instrumentation, we have more lattitude. In addition, we wanted our Study to explore the complementary role airborne reconnaissance might play with other methods of making observations — ground-based, at sea, and from satellites.

Without question, airborne reconnaissance can and has made an important contribution to our ability to provide adequate forecasting and warning to the public, for aircraft can make the mesoscale measurements in areas unavailable to ground-based or certain sea-borne meteorological measurements. We wanted to be sure that the best use was made of this national technological resource. The advent of meteorological satellites has increased, not decreased, the number of investigatory reconnaissance missions that have been flown into tropical disturbances. Alerted by the satellite, the aircraft can be directed efficiently to a suspected area to make local measurements.

The Advanced Research Projects Agency was instrumental in launching our program to design and develop the sophisticated meteorological satellites we have in orbit today, through action taken in 1958 under Mr. Roger Warner to get recommendations regarding this new potential for meteorological data-taking. As the weather service celebrates its first centennial, meteorological satellites complete their first decade — a decade wherein twenty-five weather satellites transmitted nearly two million pictures of our earth and atmosphere from "on top." We are working hard to get the most out of this technological resource. We are taking early steps toward "going operational." Aircraft, on the other hand, have been used since the early days of flying to get meteorological data at high altitudes. Yet we are not pursuing advancement in this area with the vigor needed to derive the greatest benefit from airborne surveillance of our atmosphere. We express our gratitude to the Advanced Research Projects Agency for granting its support of our study in this important and fascinating area.

We sought to define major problems and to suggest solutions. We have seen many problems. We have suggested a variety of solutions — a variety which reflects the multi-discipline structure of the group. Our suggestions range from what it appears to us can be done immediately to the more esoteric ideas which need further development.

We have not been able to suggest or to define a development program in detail. A permanent organization is needed to bring these ideas into practical focus, to define objectives to be reached in specified times, and to determine the cost: that is, to do the systems analysis.

IV. STUDY ORGANIZATION

A. Membership

Participants in our Study are listed in Appendix I. Not only represented were the many facets of operations and technology directly or indirectly connected with national forecasting and warning, but also of other appropriate technologies.

B. Seminars — Working Panels

At the outset, we held a series of seminars, with the purpose of providing for group discussion of topical problems with people who had them. Seminar topics and the theme speakers are listed in Appendix II. Later in the Study, we divided into Working Panels for purposes of preparing the material for the report. The organization of these Working Panels is shown in Appendix III.

C. Focus

In our Study, we concentrated on one type of severe storm, the hurricane, and on airborne surveillance. In our seminars, we did treat other aspects, other problems, such as convective storms, tornadoes, and coastal cyclones. We felt there were compelling reasons for using some focus of attention.

1. We believed it important to bound the Study to better fit the time we had;
2. We have had many years of experience with airborne reconnaissance of hurricanes and typhoons, experience that has delineated specific problem areas;
3. Those responsible for warning and forecasting have better characterized the information they need from airborne reconnaissance; and
4. We wanted to avoid suggesting the all-purpose system that does no particular job very well.

Having developed a system meeting the expressed and implied needs of the hurricane warning service, we are convinced that valuable applications can be made of this system to other areas. In the airborne surveillance system, we have a highly mobile and flexible task force for probing storms at mesoscale, as yet left undone by satellites or surface observations. Moreover, the principal manifestations of severe storms have almost complementary seasons, which are: for tornadoes — 1 April to 30 June; for hurricanes — 1 June to 30 November; for winter storms — 1 November to 15 April. During periods of highest storm frequency, there is minimal overlap.

D. Status Review

On August 28, the last day of the Study, we presented a status review report to invited guests. The agenda of this report and the list of attendees are included in Appendix IV.

V. DESCRIPTION OF SEVERE STORMS

A. Hurricanes

Tropical cyclone is the generic name for cyclonic circulations originating over tropical waters. When well formed and containing winds of 64 knots or over, tropical cyclones are called hurricanes in the Atlantic, typhoons in the North Pacific, baguios in the Philippines, Bengal cyclones in the Indian Ocean, and sometimes willy-willies in Australia. Hurricanes develop from "seedlings" which are sometimes observed by satellites to have their beginning over the Sahara Desert in Africa. These tropical depressions or troughs proceed in a westerly direction at speeds of around 10 knots or less.

June through November is the nominal hurricane season for the Atlantic and Gulf coasts. Early in the season, tropical storms originate principally in the Caribbean and Gulf of Mexico. Later in the year, principal areas of origin shift southeastward, from the Bahamas and Lesser Antilles on to the Cape Verde Islands. Late in the season, origins shift back into the western Caribbean and Gulf of Mexico. This area covers some 22 million square miles, much of which is accessible only to satellite and airborne surveillance and measurements.

In an average year, there will be 8.0 tropical cyclones, of which 4.8 will develop into full-fledged hurricanes, causing damage over $100 million and killing 50 to 100 persons. In a bad year, damage will exceed a billion dollars and deaths will run in the hundreds.

In the Central and Western North Pacific Ocean, there are an average of 28.0 tropical cyclones, including 20.4 typhoons. Since the advent of continuous satellite surveillance, we find that the frequency of tropical cyclones in the Eastern North Pacific is far greater than anyone had suspected. In the 1970 season, for example, 16 Eastern Pacific storms reached sufficient strength to be named, while only 7 Atlantic hurricanes developed to rate a name.

B. Severe Convective Storms/Tornadoes

The tornado occurs in many parts of the world, but rarely with the frequency it does in the Continental Plains areas of the United States. The months of greatest total frequency in this region are April, May, and June. The genesis of tornadoes in the mid-continent is the result of effects of cold dry polar air on warm moist air from the Gulf of Mexico.

Even in periods and regions of highest frequency, the annual chance that a given place will be struck by a tornado is only about one in 250, but there are many striking aberrations, including Oklahoma City, which has been struck 26 times since 1892, and Irving, Kansas, which was hit twice by tornadoes only 45 minutes apart (May 30, 1879).

The average tornado is only a quarter-mile wide and rarely runs more than 16 miles along the ground. Exceptions have been more than a mile wide and have caused heavy destruction along paths nearly 300 miles long.

The destruction caused by tornadoes is partly a result of the vortex winds well in excess of 200 miles per hour, and partly because of the sudden drop of pressure in the vortex center, which may be more than one-tenth (sometimes 0.2 or 6" Hg) the total atmospheric pressure.

The tornado death toll averages 125 per year, and damage averages $75 million. Dramatic excesses over these averages occur; for example, on April 11, 1965, Palm Sunday, 37 tornadoes killed 271, injured more than 5000, and caused property damage estimated at $300 million in the Central United States.

Two-thirds of the major destructive tornadoes are correctly forecast, but only about a quarter of all tornadoes occurring have been forecast.

C. East Coast Winter Storms/Cyclones

The East Coast winter storm is noted for the difficulty it presents to forecasters and the magnitude of the paralysis of the eastern megalopolis it can cause. These storms often form along the Atlantic polar front near Cape Hatteras, become classic Nor'easters, which develop to great intensity as they move up the Eastern seaboard and drift seaward toward Iceland to decay in arctic waters.

At the close of January 1966, a winter storm brought blizzard conditions from Virginia to New England, caused more than 50 deaths, and paralyzed the whole area for at least a day.

These storms derive their energy from the potential energy of mass distribution (interaction of cold polar air and warm tropical air) combined with intense heating of the polar air by the Gulf Stream. These disturbances become intense low-pressure systems extending over tens of thousands of square miles.

Principal forecasting problems for East Coast winter storms are the cyclo-genesis, the location and discrimination between rain and snow areas, and the problem of snow depth prediction for major metropolitan areas.

A statistical analysis for New York City has shown that nearly all heavy snowfalls are caused by coastal cyclones passing southeast of the city.

East Coast cyclone reconnaissance from aircraft has been begun only recently, the first attempts occurring in 1966-67, using a NOAA RFF DC-6. More recently, military aircraft have participated, and regular operations plans have been worked out. It is as yet too early to assess the real value of real-time, in-flight reports from a data-poor region by this airborne reconnaissance, but experience is encouraging enough to warrant further investigation.

VI. ECONOMIC LOSS FROM SEVERE STORMS

A. Hurricanes

The economic impact of hurricanes is difficult to assess. This difficulty is a result of many factors, e.g., the great variations of monetary losses depending upon the intensity of the hurricane and the area affected directly by its landfall, the difficulty in setting a monetary value on human life, the assessment of what saving has been made by taking protective action in affected areas counteracting the cost of taking that action in warned but unaffected areas, the evaluation of the loss of productivity in affected areas, etc. We were unable to treat this matter in any detail during the Study, but we present some pertinent information here in support of our recommendation of an improved hurricane surveillance system. Some of this data is

taken from a paper by Sugg,* some from reports on Camille by the Office of Emergency Preparedness, and some we received by private communication.

Because we are presently unable to do anything about either how intense hurricanes are or whether or where they touch land, we can only hope to save lives by seeking shelter or evacuation, and to reduce damage by taking protective measures. Both require credible and timely warning. The current average 24-hour forecast displacement error is about 100 miles, about equal to the average diameter of a hurricane (see Fig. 1), and the ratio of the warned to affected areas is, on the average, about 3. This means that there is a minimum overwarning now of 200 n. mi.

Large overwarned areas have at least two serious consequences. The credibility of warning, i. e., the public acceptance of warnings decreases markedly with the degree and extent of overwarning.† Moreover, vulnerable coastal areas are being increasingly built up from which there are often only single evacuation routes. It has been estimated that as many as 30,000 lives could be lost in a panic situation in one of these areas.

Today it is estimated that it costs $25 per person to evacuate a threatened area. Persons in hospitals, rest homes, and prisons would cost more. Protective measures, but no evacuation, would cost about $8 per person. Plant shutdown, airport evacuation, and the securing of resorts, fishing operations, and other coastal industries would add to the total.** If we assume that 50,000 lives were saved through the evacuation of 75,000 people in Camille, and put a life insurance kind of loss at $15,000 per head of family, $225 millions were saved at an evacuation cost of under $2 millions. This saving is affected only by the combination of credible and timely warning. The other consequence of overwarning is the cost of needless evacuation and needless protective measures. Of 2 million people in an average warning area, 2/3 or about 1.4 million are needlessly warned. If, as it is estimated, 20% of the people in a warned area take protective action, roughly 300,000 take this action at a cost of $2.4 million.

The averages used in this discussion can be quite misleading. These averages are made over a relatively small number of cases. For example, an average displacement of 100 n. mi means that there were a number of instances considerably in excess of that. If the advanced surveillance system did nothing more than reduce these individual excesses over the mean, the savings in lives and money would be significant.

Assessment of the damage losses from Camille placed the total at nearly $1.5 billion. We have no estimate of what was saved by precautionary measures. Clearly, in some areas these measures were fruitless, for no amount of protection would have prevented the loss.

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* Arnold L. Sugg, "Economic Aspects of Hurricanes," USWB Mon. Wea. Rev., p. 143 (March 1967).

† It is a matter of record that in Hurricane Camille, officials had considerable difficulty in convincing people to evacuate — forcible evacuation was done in one area. Although an estimated 75,000 people were evacuated, 145 lost their lives in coastal areas. Two other examples of mass evacuations are 350,000 for Carla in 1961 and 150,000 for Hilda in 1964.

** Report URS-792-2, "The Effects of Hurricane Camille on Industry, Public Utilities, etc," by Robert H. Black, dated March 1970 (AD 708568) gives an account of shut-down costs for many of the kinds of industry in the areas affected by Camille.

To arrive at an estimate of how much could be saved by a reduction in the maximum winds of a hurricane, we make use of some statistics used in devising a hurricane insurance loss profile. Because insurance normally does not include water damage, only damage resulting from winds is considered here. Our resulting observations will be most conservative because the surge tides, the greatest producers of hurricane loss, are also proportional to the maximum winds. In estimating the potential insurance loss per risk based on insurance surveys of a number of storms, it was found that the ratio was not proportional to the kinetic energy in the winds, but to the exponential of this energy! The data indicated that a reduction of wind speed of only 25% could effect an order of magnitude reduction in potential loss. On this basis, the savings from Camille alone would have amounted to $1.35 billion. Moreover, vulnerable coastal areas are being increasingly built up so that the future trend of hurricane property losses in the absence of effective hurricane modification will be drastically upward. The magnitude of the surge accompanying a hurricane is a function of a number of factors, among them the maximum winds, the fetch, and the ocean bottom contours. Were we able to reduce the maximum winds, we could substantially affect the magnitude of the surge and the resulting damage from flooding. Savings from reducing the surge have not been included in the above estimate.

VII. CURRENT FORECASTING TECHNIQUES – RECONNAISSANCE REQUIRED

A. Hurricanes

Forecasting techniques in use today at the National Hurricane Center (NHC) are generally empirical in nature. This empiricism is a result of years of diagnostic work done on all the storms for which we have even a modest amount of data. Principal forecasting tools are experience and judgment; experience to allow the forecaster to pull out of the past a similar set of meteorological circumstances, and judgment to permit him to effectively filter the elements of raw data he receives. Our numerical forecasting models are not yet sophisticated and reliable enough to help the forecaster with his problem storms, for while the several models generally agree on the storm that is easy to forecast, they generally are at odds on the hard ones.

While awaiting the results of experiments in tropical meteorology and the improved models that can be expected to result therefrom, the NHC plans during the next five years to "sharpen their diagnostic tools." They will attempt to automate the analysis of "symptoms" that reveal the character of the circulations, that indicate their potential for development, that reveal the trend in storm movement.

NHC forecasters now work with four computer-generated charts, which display important parameters of a simplified two-layer tropical atmosphere. Two charts show mean winds in two layers 400 millibars thick (1000 - 600 mb and 600 - 200 mb), two describe the upper and lower bounds at 200 mb and at 3000 feet above the ocean surface. The region of concern is bounded by the Eastern Pacific (120°W), the African Coast (10°W), and by latitudes 45°N and 20°S. This vast area has many data voids which are judiciously filled in by a kind of interpolation and extrapolation from real data points. There are a number of computer subroutines available to extract other derivative information from the four basic charts.

This year, for the first time, the NHC has been able to receive and process ATS-3 satellite data directly. Each day a full hemisphere picture is received every 27 minutes between the hours of 10:30 a.m. and 4:30 p.m. If a hurricane is present, half-hemisphere

pictures are received every 11 minutes between 7:30 a.m. and 7:30 p.m. After receiving five pictures, a time-lapse motion picture loop is made and studied for cloud motion which reveals winds at one or two levels. Some pictures are enlarged and formed into a special loop which expands a particular disturbance of interest, so that a radius of 6° to 8° fills the picture. This satellite data helps fill in the data voids of their charts where before the forecasters had no idea of the nature of atmospheric circulation. The satellite also serves to help direct reconnaissance aircraft to areas where the most will be gotten from the mission.

Airborne reconnaissance is needed to get the fine-grained information on the vertical motion and on conditions existing in the storm's probable path. In satellite pictures, the clouds in the outflow layer at high altitudes often obscure the low-level inflow or feeder band. To forecast a change in intensity, the location of this feeder band is important, and is now best done by the Navy's airborne surveillance radar, the APS-20. The amount of precipitation in the feeder band clouds and the direction from which they spiral into the vortex are critical items to good prognoses. Although quantitative measurements are not now asked for, the NHC does want a radar picture of the storm transmitted for local display about every 30 minutes. Transmission of radar pictures is not now possible for any aircraft in the reconnaissance fleet.

The preferred altitude for reconnaissance traverses of the storm is in the range 10,000 to 14,000 feet. In a well-formed, stable storm, winds measured at this level in the circle of maximum winds will be within five percent of those obtaining at lower levels. Usually, at 10,000 feet, less turbulence is encountered in penetrating the convective cells. In any stage of development of a storm, destructive gusts can be encountered at higher altitudes, and extreme downdrafts can occur at lower altitudes.

When a storm becomes unsteady, reconnaissance is requested at 1500 feet, or if this level must be avoided for flight safety reasons, a radial profile of equivalent potential temperature at the 300-mb level is requested by the NHC. There is an empirical relationship between the radial profile of the equivalent potential temperature just below the outflow layer and that of the surface pressure.

In summary, the preferred reconnaissance altitude for steady storms is 10,000 feet. If the storm is unsteady, the preferred level is at the base of the clouds, or alternatively, at the base of the outflow layer.

Accurate location and tracking of the storm is important because storm track forecasts are often based on a simple projection of past motion into the future, and because the storm's track is defined from the locus of the positions of its center.

In the latest operational flight plans, gradients of meteorological parameters, not point values at flight level, are emphasized. These gradients better display the configuration over a broad area. Many of the parameters called for are an indirect way of getting at the measurement of maximum winds in the storm and the radius of the circle over which these maximum winds extend.

There are a number of points of reference for the storm's center which may or may not be coincident, viz., position of lowest central pressure, center of the ring of maximum winds, center of the eye wall clouds, or center of the radar eye. Only the radar center can be located from outside the storm, and at present, that only with the APS-20 radar when storms are beyond the range of shore-based radars.

Land-based radars can detect severe storms at ranges of about 250 miles. At present, these radars give only range and track information quantitatively, and qualitative information on rainfall intensity.

B. Reconnaissance Costs

As outlined in the "Federal Plan for Meteorological Services and Supporting Research, Fiscal Year 1971," our total planned outlay including all agencies is about a half-billion dollars. Approximately $400M is required for operations, and $100M is planned for supporting research. Synoptic and tropical storm reconnaissance is included in the "Basic Meteorological Service," which totals $165.7M for operations and $71.6M for supporting research. Of the $71.6M, $63.5M is planned for satellite supporting research.

Because the several contributors to our hurricane forecasting and warning service have a number of other tasks to perform, the assessment of current costs is difficult. Operational costs of all airborne reconnaissance observations, synoptic and special, amount to $46M. Based on a survey of figures available to us, we believe the assignment of $1000 per flying hour to be conservative and independent of the type aircraft used. In a hurricane season, as many as 150 flights of an average 12 hours' duration may be required, which would cost $1.8M. The National Hurricane Center, with a staff of about 85, costs about $1.35M to operate. Contributions to the system are made by the National Meteorological Center (NMC, 390 staff, $6.0M) and the National Environmental Satellite Center (NESC, 330 staff, $5.2M). Communications services are required and a number of the Weather Bureau regional offices are involved. The Basic Weather Radar Network includes 150 radars in the U.S., 46 of which are operated by DoC at a cost of about $5.5M/yr. About one-third (16) of these are stations on or near the Eastern and Gulf Coasts and potentially contribute to the hurricane forecasting and warning service. We estimate that a pro rata share of these costs for hurricane warning and forecasting is $1.5M. Current operations then total less than $5M ($4.65M) a year.

Improved observational equipment will not significantly affect these operational costs. The principal costs would be those for development and the capital outlay for procurement and installation.

VIII. FINDINGS

A. General

The picture we get of contemporary operations is one of dedicated people doing incredibly well with limited available technical resources. There are many examples of ingenuity and enterprise in the turning out of needed prognoses by squeezing enough pertinent information out of a sometimes balky atmosphere and surveillance system. However, it is clear that much can and should be done to meet the President's request that appropriate aircraft and the best available equipment be used in the future.

For example, none of the aircraft currently used for air weather reconnaissance observations was designed for that purpose. The Navy employs the EC-121 (Fig. 3), an aircraft system designed during World War II for the purpose of providing airborne early warning for fleet units. The WC-130 employed by the Air Force (Fig. 4) for its reconnaissance missions was designed as a cargo craft and modified insofar as was possible to meet the requirements of its new task. The DC-6 aircraft used by the Research Flight Facility (RFF) (Fig. 5) was designed as a passenger plane. With the exception of the WC-130, these aircraft

are obsolete or obsolescent. The aircraft, themselves, and the equipment aboard them are becoming increasingly difficult to maintain and to keep in a state of readiness for missions.

The best plan view hurricane pictures available today are made with a radar designed during World War II, a radar out of production for over a decade, a radar carried aloft on an airborne system designed to do airborne early warning for fleet defense. The APS-20 operates on the right wavelengths for the job; the radar has lots of power, a large antenna, and a 360° view of the storm, but as we try to put this system on available aircraft other than the EC-121, we find that the essential component for adequate resolution, the large antenna, cannot be fitted on these other aircraft with the expectation that it will still be air-worthy in a hurricane. The APS-20 is not a coherent radar, nor does it use incoherent techniques to provide a measure of wind velocity or other Doppler-related parameters.

> It must be emphasized that the transfer of the APS-20 radar to other aircraft without keeping the large antenna used on the EC-121 will seriously degrade the performance of this system in hurricanes, yet this transfer will take place in each instance of aircraft replacement.

We know that current operations are not carried out with the advanced technology we believe is available. There are a number of measurement techniques demonstrated in a laboratory or research environment that could provide important operational information to the forecaster but are not yet developed for operational use. In some instances, the transposition from research to operations would involve but small effort and cost. In others, extensive development is indicated to demonstrate operational effectiveness. However, we must implement operational solutions with due regard for performance, reliability, and field maintainability. Self-checking features must be built in. Spares must be ordered at the time of the original purchase. We must also continually remind ourselves that just because a subsystem operates well on the ground or in some other vehicle does not guarantee that it will work well on an aircraft. These systems have to be designed for aircraft, developed on aircraft, and tested on aircraft, before a recommendation can be made that they be a part of an operational system.

We are not getting all the information we should be getting from our ground-based systems. In particular, in those critical hours before landfall, the radar should be able to give us information as to the winds in the storm, as well as its position. We are well aware of the difficulties of doing a demonstration development with a component of the operational system. We know also that a development program at a given fixed installation would have little probability of getting the needed extensive experience with actual hurricanes. This development must be done with a mobile system, one that can be air-lifted or helicopter-borne into threatened areas, where it will have the opportunity of studying every storm that comes within range of our coastline. To save development costs, the conversion of FAA radars should also be explored.

We have not been exploiting the full potential of satellite observations. Some information gotten now by satellites is not directly sent to forecasting centers. This year, the NHC has implemented a facility to enable them to use satellite cloud pictures in a time-lapse movie type of "change detection" for velocity measurements on upper cloud layers. We understand the reluctance on the part of the developers to insert data from unproven measurement techniques into an operational situation, but there is evidence that this attitude has at times been excessively conservative. We have a major national investment in satellite

measurements from which we must continue to derive maximum benefit from the synoptic scale observations possible as supplemented by the mesoscale details available from aircraft. Infrared measurements,in particular, should be utilized to give data on ocean areas in advance of the hurricane's track.

B. Operations

Severe storm surveillance by airborne reconnaissance is a challenging and demanding task for the operators. There is nothing quite like it in other kinds of military operations. It takes time to build the special skills needed to make a man an effective part of the airborne reconnaissance team. Standard military rotation practice, with periods as short as two or three years, makes it almost impossible to acquire the needed long-term experience for this very specialized task.

Today's reconnaissance aircraft often encounter considerable difficulty in performing their missions in areas having commercial or private air traffic. A "no known traffic" report from a control center is little consolation to the flyer in a severe storm. We believe severe storm reconnaissance is important enough to warrant high-priority usage of air space to get essential data.

It is now necessary for reconnaissance aircraft to penetrate the hurricane to get needed data. Flight safety factors and sometimes prudence prevent an aircraft from completing all elements of its mission. These incomplete missions often occur at times when the loss of data is the most detrimental — times when the hurricane has developed into a very severe storm. The apparent incompatibility of an airframe that can penetrate these severe storms with a measure of impunity and a radome of a size that will provide adequate radar performance has given us much concern. We therefore find it important to try to get needed information remotely without actual penetration.

Today we cannot take needed forecasting and warning data on hurricanes from high-altitude aircraft. We are missing significant advantages of high-altitude flying, among them, the advantage of being above the weather, therefore encountering none of the turbulence or other stress conditions existing at lower altitudes; another advantage is that derived from being above commercial air traffic patterns — hence avoiding air traffic control problems mentioned above.

C. Radar

Present radars do not use even the most elementary moving-target indication techniques. There are ways of finding out with existing radars how fast and in what direction the meteorological targets, hydrometeors, are moving. One is the observation of the change in position of a rain cell with time on a plan display. A sequential set of these displayed in a manner analogous to a time-lapse motion picture gives the essential displacement velocities. Doppler measurements can be made, even with an incoherent radar, by comparing returns from two antenna beams. Some FAA radars now use Doppler techniques and could provide emergency storm information with minimal alteration.

D. Communications

The forecaster is all but "out of touch" with elements doing storm reconnaissance for him. Communication circuits are now roundabout and can involve costly delays or produce misunderstanding between the user and the observer. The forecaster often cannot call for changes reflecting new information he has from other sources, nor can he call for important

verification of data which might well be accurate but presents such a departure from "normal" that it is questioned. Direct, real-time intercommunication is essential to getting the most out of our reconnaissance missions. If necessary, the data rate can be kept small, e.g., a single voice channel. Relay of the important features of the radar display can be of great assistance. Even the relay of a television view of the storm as the reconnaissance aircraft sees it is technically feasible, but we were unable to verify that its inclusion in contemporary or near-future systems would be worth the cost.

We are not yet making effective use of satellite communication systems in our severe storm forecasting and warning. A key to effective weather forecasting has always been good communications. As weather patterns move in the atmosphere, the situation for one area becomes the principal element in the forecast for another. Hurricane and other severe storm reconnaissance is often done at such long ranges that the only communications possible other than through satellites is with HF links. To improve the quantity and quality of communications, satellites should be used with severe storm surveillance systems. It is important, however, to establish dedicated circuits for the exclusive use of these reconnaissance aircraft during storm emergencies. Satellite communications also provide the opportunity to establish direct channels to those centers responsible for forecasting and warning.

An equally important area is the communication of alerts and warnings to the general public. Warning centers now rely on operating through the news media and in some areas, by broadcasting in the VHF weather band. Special receivers are required to get the VHF broadcasts. We believe it preferable to assign one of the FM broadcast channels to each Weather Bureau region for purposes of relaying alerts, warnings, and forecasts to the public.

E. Navigation

An essential element in airborne reconnaissance is good navigation. Today's operational systems, which rely heavily on Doppler radar navigation systems, encounter difficulties when flying in or in the vicinity of hurricanes. Confusion caused by radar scatter from moving water or blowing rain can contribute substantial errors in navigation. Inertial navigation systems for airborne use, both commercial and military, are in an advanced state of development, and there are a number of very good systems in current operational use. With Omega or Loran navigation systems, where their coverage is appropriate, we have the opportunity to provide an ingredient that many inertial systems need, viz., period updating of the system, which has been subjected to the natural drift and cyclic variations.

F. Data Processing

Our approach to data processing in current reconnaissance aircraft is primitive indeed. Currently, for example, dropsonde data is reduced by hand aboard the aircraft. In the near future, this operation will be speeded up by the installation of a desk calculator. The Navy is equipping its aircraft with a data logging system, which is a commendable step in the direction of increased automation in data handling and meteorological message composing, and is the most comprehensive system in operational use today. There are a number of small, air-qualified, digital computers available. We must take advantage of this opportunity to use this first-rate equipment to aid in the processing, the logging, and the preparation for transmittal to the ground stations of meteorological data. Moreover, the digital computer is an essential element in advanced radar technology.

The number and kinds of measurements necessary for forecasting today are excessive. The forecaster is confronted with information taken with a variety of instruments, in a number of different situations, from what current measurements indicate is going on now at a number of different levels and scales, to what history can tell us about the behavior of similar storms in the past has been, and what our forecasting computer models are indicating as a prognosis. Because of the vagaries of our instruments, our environment, history, and our models, all these elements do not always agree. The forecaster has to "filter" conflicting information.

We do not now, for example, cross-calibrate instrumentation on the various elements of our reconnaissance fleets. Moreover, we have no instrument calibration center where important checks can be made. The amount of data called for will continue to be excessive until the reliability of key observations can be adequately demonstrated.

Much meteorologica data is redundant. Today's forecaster uses this redundancy to enable him to cast out misleading or incorrect data from faulty observations or instruments. As we can improve the accuracy of our data, we can lessen the need of redundancy and concentrate on parameters essential to forecasting. Radar data, like satellite data, can contain more information than the forecaster can use. It is more important to get essential information to the forecaster in a short time than to give him details. Airborne digital computers can help with this sifting task.

G. Research

Detailed recommendations in this area appear elsewhere in this report and discussion is contained in the Panel Report. We highlight some of the findings here.

A most important research area is that related to storm modification. The ultimate response to the hurricane threat is effective modification. Current results of hurricane modification experiments are encouraging. A number of limitations on current operations ranging from storm frequency to available funds have not permitted pursual of this important area with sufficient speed and emphasis. Current forecasting and warning techniques have dramatically reduced the numbers of lives lost in hurricanes, while property loss has risen by staggering amounts. Only a modest weakening of the maximum winds of a storm would make a substantial reduction in storm damage. We are convinced that surveillance systems play a vital role in enabling us to make an active rather than a passive defense of our lives and property. Moreover, there are a number of fringe-area technologies that might well be applied to the problem of hurricane modifications.

Operational observations as made today have little real value for research. Many of the observations are qualitative or of questionable accuracy. Even when observations and measurements are of high quality, they are often not recorded and correlated with time and aircraft location, or recorded in a format that permits later reconstruction of the events. On the other hand, there is such a paucity of data that researchers have gone to great lengths to recover as much information as possible from observational flights. Even our research aircraft suffer badly in this respect, especially in the radar area. Obsolescent aircraft make research operations difficult and maintenance a headache. Research aircraft should be at the forefront of technology but in the case of radar, they are significantly behind the WC-121 because the antenna size has been reduced on the APS-20 search radar, and the height finder has a much smaller antenna than the APS-45 used on the WC-121.

A study should be made of the mass psychology of alerting and warning. At present, we can do little in defense of our property against violent storms, but we can hope to save lives by providing credible warning in time for people in the affected areas to seek and attain shelter. Public acceptance of these warnings and a willingness to react to them is strongly dependent upon local and personal credibility. Acceptance is also dependent upon a public informed of the personal danger involved.

Warnings of a conservative nature include a large number of people who might be endangered, are safe in the sense that it is highly unlikely that anyone seriously affected would not have had warning, but excessively conservative warnings have a negative effect on the scores of people in the peripheral areas who evacuate needlessly, who resent the "needless" imposition on their time, effort, and money.

The human factors problem is to word the advisories so that the necessary conservatism of the forecast, pending better methods, will not desensitize the public to the next alert of possible danger, so as to produce rational reaction to warnings, and to avoid panic.

As hurricane-vulnerable areas are increasingly built up and populated, the call for evacuation of large areas can become a more and more difficult decision. In areas served by but a single evacuation route, a panic reaction can cause carnage on the highways, leaving those unable to evacuate because of clogged exits to fall victim of the storm.

Today, certainly, our only defense when threatened by a violent storm is to seek personal safety, to seek shelter, and to secure our property as best we can against the storm, or to remove ourselves and those of our belongings that are portable and mobile.

IX. ADVANCED HURRICANE SURVEILLANCE SYSTEM

In the block diagram of Fig. 6, we show a system concept. Included are the subsystems discussed in our recommendations. An important feature of this system is direct communication between reconnaissance elements and the NHC. We have shown a dotted attachment of the meteorological and communications satellites because eventually they can be the same satellite.

A number of iterations of the reconnaissance aircraft subsystem are shown in Fig. 7, and a similar matrix for radars in Fig. 8. The goal of the major modifications to prospective reconnaissance aircraft is to provide a large steerable antenna, the key to high-resolution radar performance. The options range from minimal changes through substantial modifications of existing aircraft (Figs. 9 and 10), to an advanced high-altitude surveillance system (Fig. 11). A goal of the high-altitude system would be to get needed data without penetrating the storm.

An important element of the system is an advanced air-transportable ground station, employing Doppler radar and other novel measurements techniques. The mobility of this station would enable us to position it in or near the path of threatening hurricanes or other storms to gain more experience and data than could be gotten by similarly equipping a single or a few ground stations. This system would not only track the storm, but also would measure winds and rainfall during the critical period twelve to twenty-four hours before landfall. Operational data would be transmitted directly to the NHC. Research data would be recorded for later use.

The system allows growth without disruption of an operational system. Advanced prototypes can be tested in parallel with current operations, then included in the system in an orderly fashion once the concept has been proven.

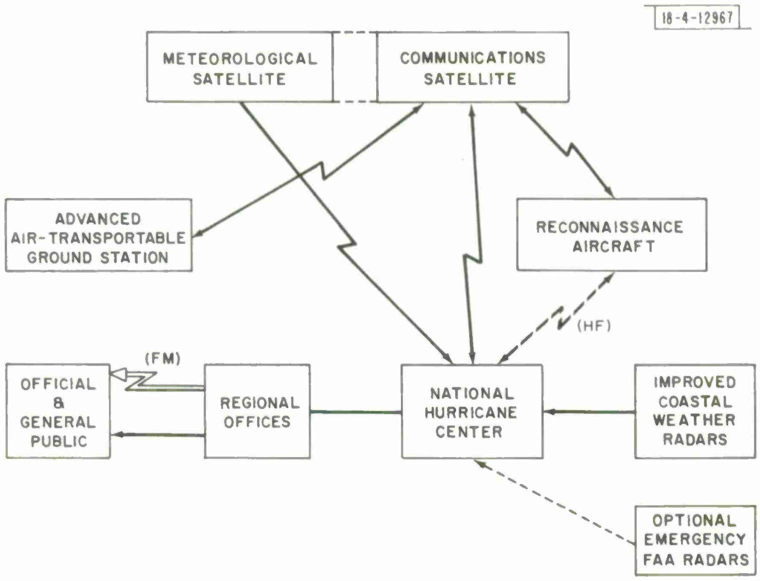


Fig. 6. Hurricane surveillance and warning system.

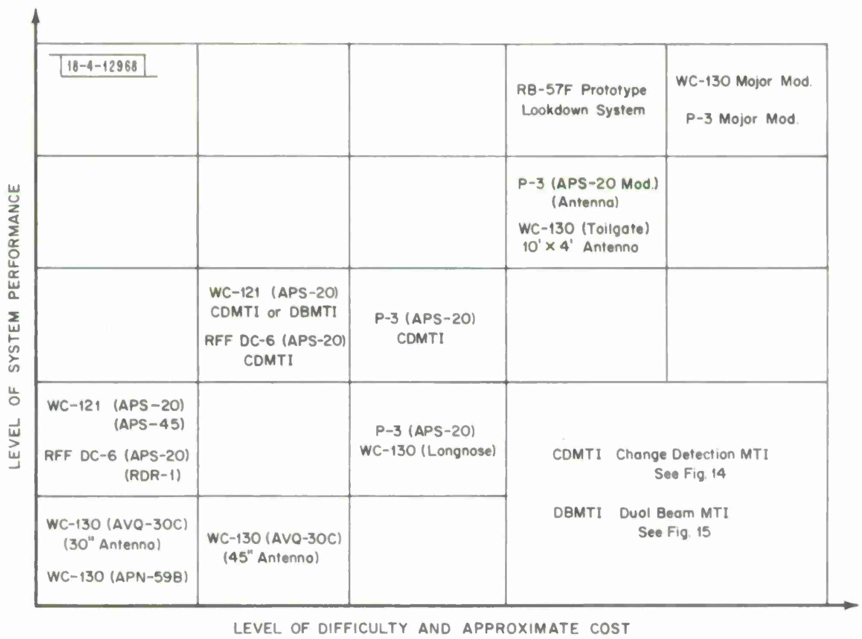


Fig. 7. Reconnaissance aircraft matrix.

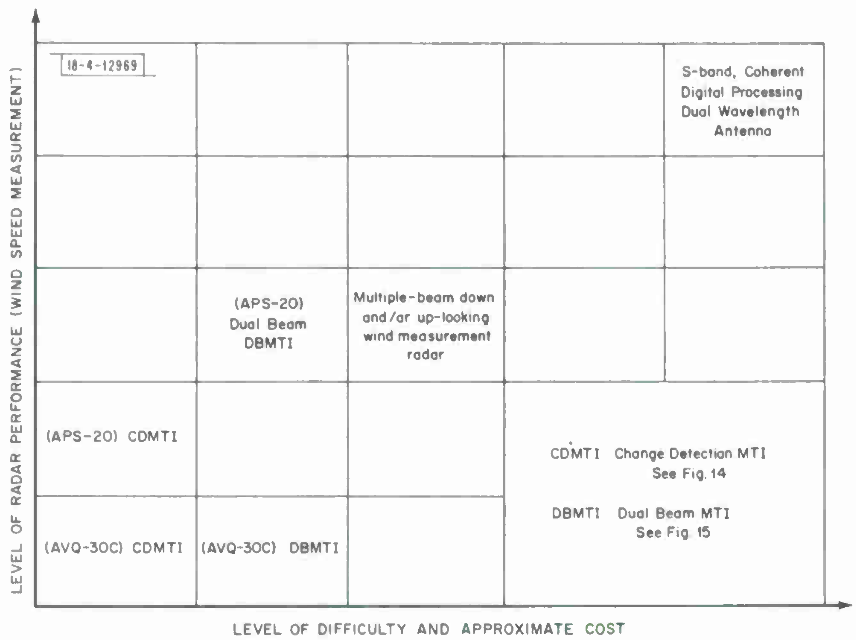


Fig. 8. Reconnaissance airborne radar matrix.

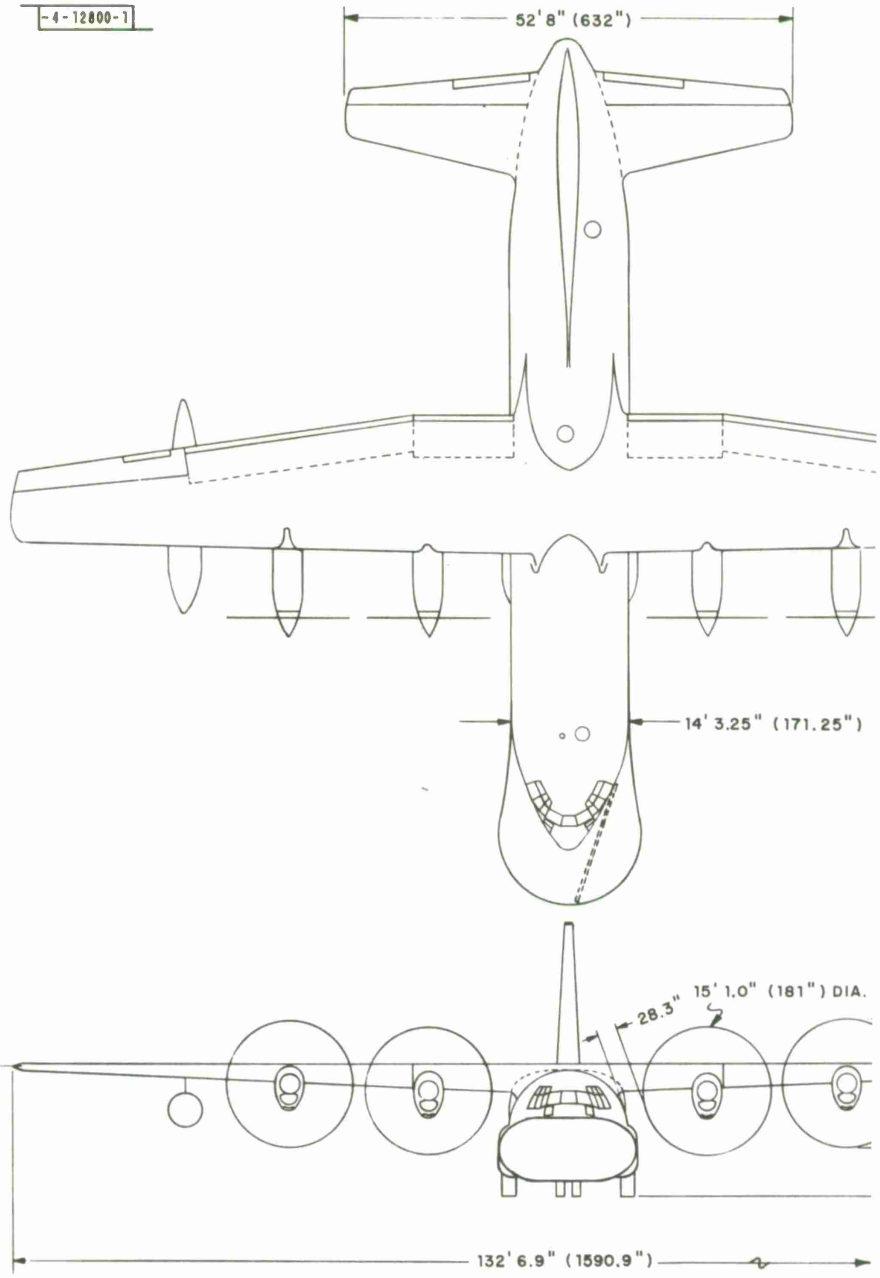


Fig. 9. WC-130 nose modification suggested in Lincoln Laboratory Study. The enlarged radome would accommodate an antenna approximately 16 feet wide by 7 feet high which could scan 140° in the forward sector.

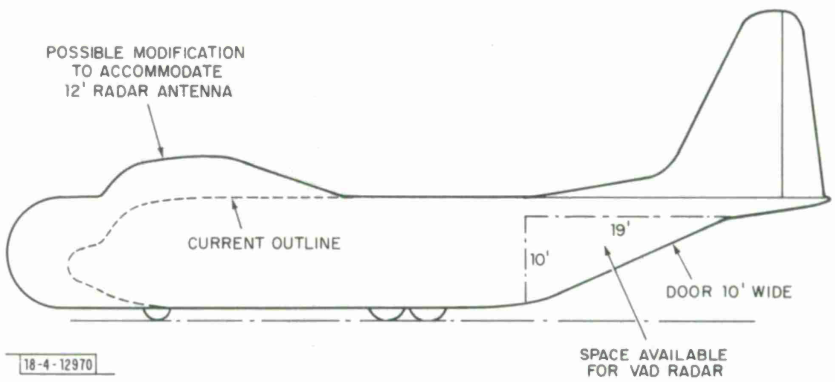


Fig. 10. Possible "guppy-like" modification of the WC-130 to permit installation of a large forward-looking antenna. Horizontal scan $\pm 90^{\circ}$; vertical scan nadir to zenith. (VAD: Velocity Azimuth Display Radar; see Fig. 16.)

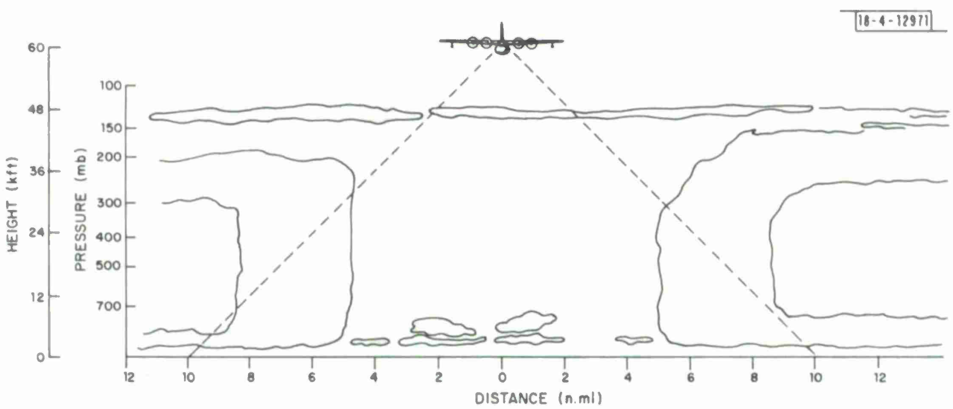


Fig. 11. High-altitude look-down radar reconnaissance of a hurricane.

Major subsystems of the airborne system are:

Meteorological Sensors (Flight Level/Remote)
Dropsondes
Radar with Digital Signal Processing
Navigation
Data Processing
Display
Data Message Composer
Communications
Data Storage and Recording

Major subsystems of the advanced ground station are:

Radar with Digital Signal Processing
Data Processing
Display
Data Message Composer
Communications
Data Storage and Recording

A. Advantages of Very-High-Altitude Storm Reconnaissance

1. Operational

   a. Above severe turbulence in most violent storms;

   b. Above major air traffic patterns, hence, fewer restrictions by air traffic control on operational patterns;

   c. Can serve as control aircraft for low-level operations by drones or manned aircraft.

2. Radar (Look-Down)

   a. Large look-down antennas can be installed in the high-altitude aircraft providing:

      i. High resolution at longer wavelengths;

      ii. Potential for interlaced and multiple wavelength systems.

   b. Since scattering and attenuation increase from light to heavy with range, no weak targets at long ranges need to be detected through heavy precipitation.

      i. Radar returns from weakly scattering cirrus tops are viewed from short range;

      ii. Clutter from sea surface outside the range interval where storm measurements are made.

   c. Limited radar range required.

      i. High PRF — large unambiguous Doppler velocities.

   d. Less turbulence encountered.

      i. Aircraft motion compensation less difficult;

      ii. Doppler frequency spread reduced.

3. Instrumentation

   a. Wide-angle cloud camera or TV surveillance of storm from above;

   b. Better IR surveillance from top;

   c. Radar track and interrogation of dropsonde throughout flight;

   d. Since aircraft will encounter less turbulence, platform stabilization and motion compensation will be less difficult.

4. Communications

   a. Real-time, high-capacity data link possible via wideband, short-wavelength, up-link to advanced COMSAT from high altitude where atmospheric attenuation is minimal;

   b. Small antenna on top of aircraft at short wavelengths can give high-gain up-link;

   c. Sophistication can be put into ground terminals rather than aircraft where weight and power restrictions are not as severe.

B. A Suitable Airframe for Very-High-Altitude Storm Reconnaissance

In the RB-57F (see Fig. 12) we have an existing high-altitude airframe with suitable performance characteristics for development and test of a prototype system.

X. OTHER AREAS OF APPLICATION

A. East Coast Winter Storms

For the past few years airborne reconnaissance has been increasingly used to fill data voids existing in offshore areas frequented by tracks of winter storms. The advanced system will offer the forecaster an even richer data base to help him with his difficult prognoses for the coastal megalopolis.

B. Severe Convective Storms (Hail, Tornadoes)

So far, the need of operational airborne reconnaissance data for these storms has not been defined in the detail it has been for hurricanes and east coast winter storms. Nevertheless, doppler or pseudo-doppler radar techniques developed for either airborne or ground-based use in hurricanes should be directly applicable to tornado detection. There is an urgent need to identify reliable tornado radar signatures. The area encompassed in current tornado warnings is far too large and must be reduced to improve credibility of these forecasts.

The airborne surveillance system can have a great impact on monitoring the severe local storms, improving their predictability, enhancing our understanding through research, and ultimately, perhaps, providing the necessary observations and control for modification. Should the National Hail Research Experiment prove the feasibility of hail inhibition, it will be necessary to provide an airborne observing system to be dispatched to threatened areas for purposes of monitoring and control of seeding, something that cannot be done from the ground.

C. Air Traffic in Bad Weather

Efficient use of terminal airspace when storms are in the area is a function of the precision with which we can define dangerous regions. A lot of otherwise useful airspace is now lost, because in the absence of well-defined danger areas, air traffic control has to

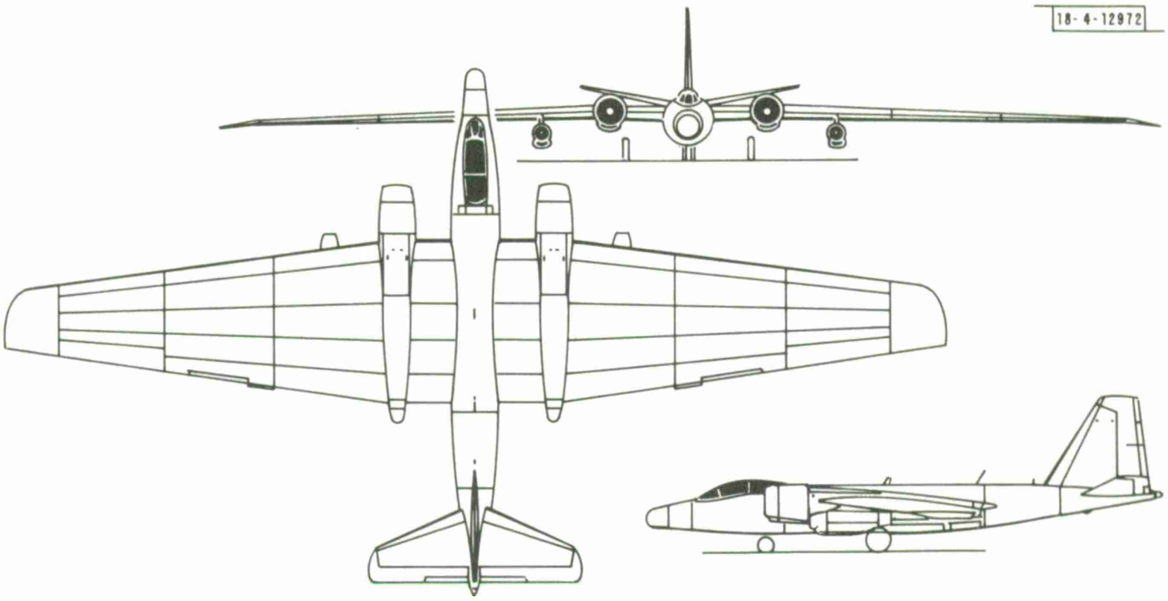


Fig. 12. Three-view drawing of General Dynamics RB-57F.

be conservative.

En route, it is current practice to designate broad areas infested with storm cells as regions to be entered only at the carrier's risk. Better definition of en route weather can reduce the size of these forbidden areas thereby speeding the flow of traffic by requiring fewer deviations.

Airborne surveillance, especially that from "on top" can provide high resolution air-lane patrol, and terminal airspace reconnaissance.

D. Weather and Storm Modification

Applications in this area have already been discussed elsewhere. Airborne surveillance serves in all facets of these efforts: Research data for understanding, reconnoitering for appropriate location to try modification, command and control during modification operations, and assessment of results of modification attempts.

XI. ESTIMATED COSTS OF AN IMPROVED SYSTEM AND ESTIMATED SAVINGS TO BE DERIVED FROM SUCH AN INVESTMENT

A. Communications Satellite

The design and launch of a synchronous communications satellite would cost from \$10 to \$15 million. However, as indicated with dotted lines on our overall system diagram, the meteorological and communications satellites may be a single synchronous platform in the future. The Synchronous Meteorological Satellite (SMS), scheduled for launch by NASA in 1972, will be operated by NOAAas the Geostationary Operational Environmental Satellite (GOES). This satellite will support a large number of data-collection platforms (approximately 10,000) by relaying their data to the Command and Data Acquisition Station on command. This data will be transmitted over a UHF link (approximately 400 MHz). The GOES system will also have a photo-facsimile (PHOTOFAX) and weather chart (WEFAX) relay operating at S-band. This 1690-MHz system will use the same modulation format employed in current Automatic Picture Transmission (APT) satellites, and should prove quite useful in relaying reconnaissance aircraft, and the transportable ground station data and radar pictures. A station now equipped with an APT receiving system would need only an S-band-to-VHF converter to make full use of the GOES link. The National Hurricane Center, for example, now has this capability.

B. Reconnaissance Aircraft

In Figs. 7 and 8 we indicated in a qualitative way the level of performance as a function of system cost in the several possible growth alternatives. The bulk of the cost in any of these systems will be that involved in providing a large aperture on the aircraft. The Navy has estimated that the modification of six aircraft to accommodate a smaller APS-20 antenna in the bomb bay of the P-3 aircraft, the reconfiguring of the aircraft for meteorological measurements, and the installation of the APS-20E radar from the WC-121's, will cost \$68 million. The Air Force has estimated that a WC-130 major modification (e.g., a large radome or rotodome) plus a new radar and associated equipment would cost from \$20 to \$25 million for development of the first one, and has concluded that in production, the cost of radar and rotodome would be \$1.5 to \$2 million each. It is reasonable to assume that a comparable modification of the P-3 plus a new radar would involve comparable cost. Research on and development of a prototype radar for test of the high-altitude, look-down reconnaissance concept in an RB-57F aircraft would cost between \$2 and \$5 million,

depending upon how complete a prototype of the total system this experimental model has to be.

C. Advanced Air-Transportable Ground Station

Based on recent development costs of air-transportable tactical radar units, we believe that an experimental prototype of this versatile ground station could be built and readied for test for between $2 and $3 million. It is envisioned in determining these costs that a tube such as the VA-87 could be used in the coherent radar system and that, therefore, no major power tube development would be necessary. This unit would be the test vehicle for a number of measurement concepts which may later be recommended for installation in all coastal radar systems. It is also expected that a significant amount of equipment for this experimental system could be furnished by the government, equipment that has reached an advanced stage of development and is ready for experimental systems test.

D. Cost Summary

Subsystem	Min. Cost	Max. Cost
Communications Satellite (2)	0	$ 30M
Reconnaissance Aircraft		
Medium-Altitude Penetrator (10)*	$100M	$200M
High-Altitude Experimental Prototype System (RB-57F)	$ 12M	$ 25M
(1) prototype† $2 to 5M		
(2) operational $10 to 20M		
Air-Transportable Ground Station Experimental Prototype	$ 7M	$ 13M
(1) prototype $2 to 3M		
(2) operational $5 to 10M		
Totals	$119M	$268M

We believe that for this investment we can have a substantially improved hurricane surveillance system in which we would more fully exploit the data-gathering potential of penetrating aircraft, and also, promising new ways of measuring important storm parameters can be tested under actual storm conditions, while at the same time making real-time contributions to operations supporting forecasting and warning.

E. Savings by Reduction of Forecast Differential

In our earlier discussion of economic loss from hurricanes, it was pointed out that today only twenty percent of the people in a hurricane warning area take protective action. Based on the estimate that one hundred miles is the effective diameter of a major storm

* The estimated requirement of ten aircraft of this type is probably high. The actual number required would depend on total system operational reliability and the number of simultaneous storms to be accounted for.

† If the prototype high-altitude system proves successful, operational high-altitude units would replace most of the penetrators.

and that one hundred miles is the forecast differential, two thirds of the people in a hurricane warning area will needlessly be warned (or "overwarned"). If we achieve our goal of a reduction of the differential to less than 50 miles, the overwarned would be reduced to one half. The credibility of warning in the affected area is greater, which would be expected to encourage more people to take precautionary protective measures. Most important, increased credibility would cause more people to heed evacuation warnings in time to save lives and portable property.

Each person's share of the gross national product ($1 trillion/year ÷ 200 million people) is $5,000 per year, or for each family of four: $20,000/year in goods and services from the approximately 200 productive days per year. We therefore estimate that $100/day is the average productivity for each family of four.

Population densities on the eastern seaboard and gulf coasts vary greatly, but we estimate an average number of 5000 people per mile of coastline to a depth of 20 miles inland. In a 300 to 400-mile warning area, 1.5 to 2.0 million people are warned, of whom today 1.0 to 1.3 million are overwarned. These figures could be cut to a half million if the differential were reduced to 50 miles (100-mile affected area, 100-mile overwarned area) resulting in a reduction in those overwarned by as many as 800,000. These 800,000 people represent 200,000 families making a $100/day contribution to the gross national product for a total of $20 million a day. If we assume that only a half day's productivity were lost per storm as a result of the overwarning, the savings realized by reducing the differential to 50 miles is at least $10 million per storm.

Twenty percent of the 800,000 or 160,000 took needless protective measures costing at least $800,000. On the other hand, 80 percent of the 500,000 people in the affected area took no protective measures and as a result suffered $100 per person preventable loss, or $40 million.

This crude estimate, based on the loss of productivity and lack of protective measures, shows that a reduction in forecast differential from 100 to 50 miles would save at least $50 to $60 million per storm, of which we average a little more than one a year. We therefore give $75 million per year as an estimate of the total savings to be realized.

Population densities in these coastal areas are increasing. The histogram of devastating hurricanes (Fig. 13) shows that as the number of vulnerable areas increases, the number of hurricanes we have to consider dangerous also increases — especially noteworthy are the last thirty years.

If we amortize a $250 million capital investment in improved reconnaissance over 5 years, there still remains $25 million a year for operations. The investment appears economically justifiable on this basis alone.

F. Savings in Other Areas

We have not taken into consideration other important applications of an advanced reconnaissance system. Hurricane operations would extend over a period of not more than six months, of which we could expect peak activity during the months of August, September, and October. At other times elements of the system could be deployed to meet other needs such as East Coast winter storm reconnaissance during the fall and winter, and investigations of hail and tornado-producing thunderstorms in the spring and early summer. In fact, the system capital cost should be prorated over these other services, and if this is done, the development of the system is even more worthwhile. We have not done this here because the monetary value of improved forecasts in this area are even more difficult to assess.

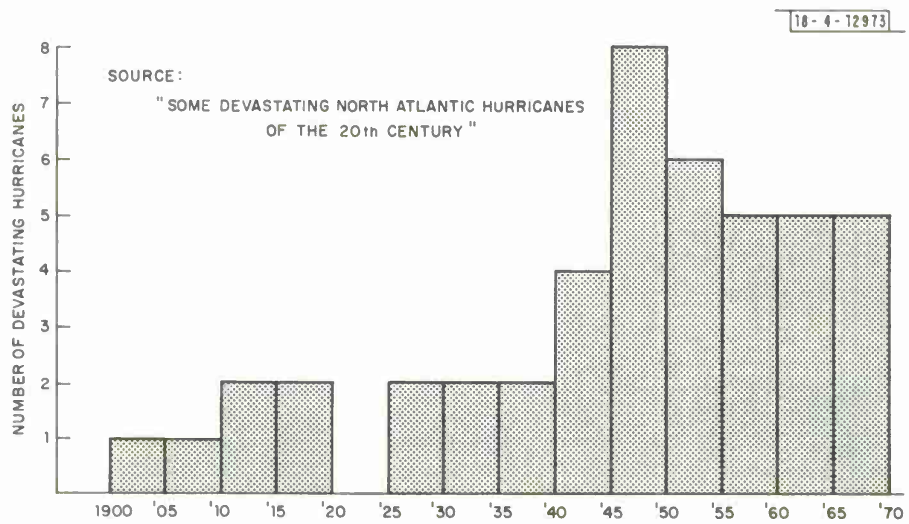


Fig. 13. Frequency of devastating hurricanes in half-decade periods, 1900-1970.

XII. DETAILED GENERAL RECOMMENDATIONS

Our specific recommendations fall into three general categories:

1. Short-term improvements to the present system;
2. Promising ideas, systems components, and alternatives for consideration in a future hurricane warning service systems analysis (and future system engineering) to develop an improved hurricane warning service; and
3. Research recommendations.

A. Consensus

While the technical panels emphasized in their recommendations factors involved in their specialized areas, a number of ideas were pervasive. The following recommendations have the general consensus of the group, and offer immediate initial responsiveness to the President's request.

1. Move immediately to improve the quality of meteorological data taken by airborne systems. Provide individual calibration of aircraft air data systems. Establish uniformity in measurement techniques, calibration, and format, of all reconnaissance aircraft in the operational fleet. Ensure better commonality of measurements by employing simultaneous calibration flights of aircraft from all units involved in hurricane reconnaissance. Take the necessary steps to improve our use of sondes and bathythermograph equipment in the hurricane environment.

2. Provide direct and real-time communications between reconnaissance elements and the center responsible for forecasting and warning. Establish voice communication links between reconnaissance aircraft and the National Hurricane Center for:

   a. Faster transmission of high-priority data;
   b. Requests for additional data and revision of flight plans;
   c. Verification of questionable data and discussions. Transition from high frequency to satellite communications to improve long-haul reliability and to increase available bandwidth. Establish dedicated circuits for use during storm emergencies. Provide real-time still pictures of radar and possibly, visual observations to warning centers. (Automatic picture transmission [APT] techniques might be used to lessen bandwidth required.) Seek allocation in the FM broadcast band for Weather Bureau broadcast of warnings and information of the kind now broadcast on their VHF broadcast service.

3. Improve navigation systems in operational reconnaissance aircraft. Install inertial/Omega navigation system.

4. Establish FAA air traffic control priority for storm reconnaissance aircraft. In the face of rising worldwide aircraft traffic, a high priority will be essential to enable the aircraft to get the necessary reconnaissance data.

5. We recommend a study of the mass psychology and human factors problems involved in alerting and warning of the public on the occasion of threatening severe storms.

XIII. SPECIFIC PANEL RECOMMENDATIONS

Meteorology Panel

The following is a priority list for measurements of tropical cyclone parameters:

Priority	Parameter
1.	Location of center
2.	Central pressure
3.	Wind-area grid
4.	a) Maximum wind b) Eye diameter
5.	Radius of maximum wind
6.	Wind profile
7.	D-value profile
8.	a) Temperature profile b) Mixing ratio profile
9.	Sea-surface temperature grid
10.	a) Precipitation intensity (eyewall) b) Precipitation intensity — radar reflection (area grid) c) Height of eyewall
11.	Tide anomalies
12.	Swell
13.	Gustiness, tornadoes, turbulence
14.	Bright-band height profile

The following special recommendations are made in order of priority:

1. By radial profile measurements, locate the hurricane center to an accuracy of about 5 n. mi, defining this center as one of the following:
   a) The center of the ring of maximum surface winds;
   b) The point of minimum sea-level pressure.
2. Measure the intensity of the hurricane from:
   a) The lowest value of sea-level pressure;
   b) The wind speed in the zone of maximum winds.
3. Supplement the wind-area (3° latitude grid) measurements with vertical wind soundings. The scales of observation must be chosen to fit the needs of forecasts with regard to both space and time. Example: For forecast of maximum winds prevailing in a hurricane, the representative period of wind observation should be about one-half to two minutes to smooth out the turbulence. Implement recommendations on items of high priority before investing a lot of time and effort on low-priority items.

Platform Panel

A. Immediate Application

We recommend:

1. Individual flight calibration of aircraft air data systems (static pressure, temperature recovery factor);
2. Review of manual data-handling procedures for AN/AMT-13 dropsonde, to see if simplification is possible;
3. Addition of velocity — G-load (z-axis) — height (altitude) (VGH) recorder to all aircraft;

4. Modification of Doppler inertial navigation system in P-3 prototype aircraft to include manual switch for maintaining inertial operation. Flight test of the system for accuracy in hurricane environment;

5. Observation of Omega accuracy in hurricane conditions.

B. Near-Future Application — Current Airframes

We recommend:

1. Commonality of equipment, criteria, and procedures to the degree possible;

2. Changing the RFF fleet to a standard airframe (WC-130 recommended, WC-135, if needed), including basic Air Force instrumentation;

3. Installation of inertial navigation and Omega in all aircraft, and testing in hurricane environment. The use of inertial system to record accelerations for turbulence measurements;

4. The study of autopilot modification to permit full automatic flight control during turbulence.

5. The development of a combined calibration chamber — launch tube for dropsondes for in-flight, pre-launch calibration at two or more reference points;

6. Investigation of the aerodynamic characteristics of dropsondes as a function of desired measurements and method of accomplishment, since sonde requirements may be different within and outside the eye. Completion of current development programs with airborne tests;

7. Experimenting with stationing balloons and buoys within the eye by air drop;

8. Conducting human factors studies for operations in current air frames and design criteria for future airframe selection.

C. Long-Term

We recommend:

1. Immediate start on the design and development of a high-altitude airborne system for severe storm surveillance, with emphasis on compatibility between the airframe and its payload of sensors and other system components, with the aim to ultimately avoid penetrating the hurricane, by reconnaissance aircraft;

2. Instrumenting an RB-57F for over-the-top reconnaissance to test high-altitude observation potential. Pursue vigorously the development of airborne system prototypes with operational use objectives;

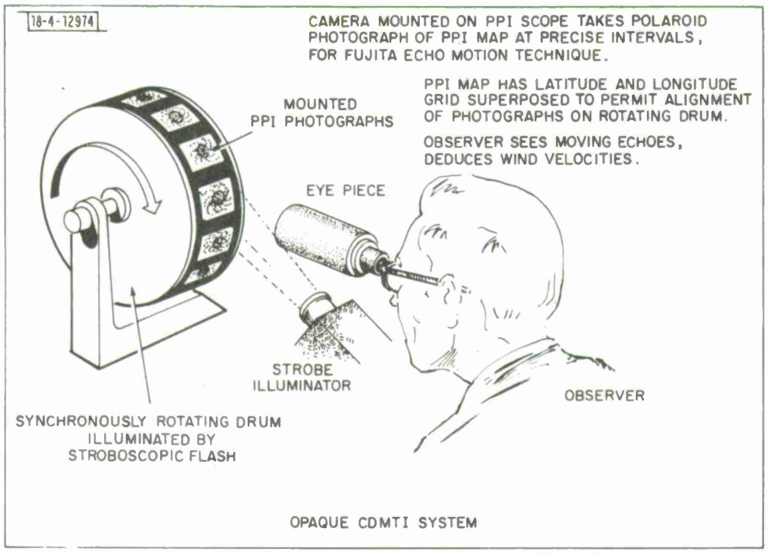
3. Transmittal of meteorological reconnaissance requirements, including flight envelope and radar criteria, to groups studying advanced airframes destined for other purposes (e.g., AWACS);

4. Continuous review of applicability to weather reconnaissance of both advanced work (AWACS) and current airframe characteristics and availability (e.g., C-141 and C-5), as part of WRX studies;

5. Budgets which permit major modification of existing airframes specifically for meteorological purposes, if trade-off studies of required characteristics (e.g., antenna versus airframe) have demonstrated need.

Radar Panel

We have in our recommendations placed some emphasis on low-cost modifications to existing ground radar systems to fully exploit their latent potential.



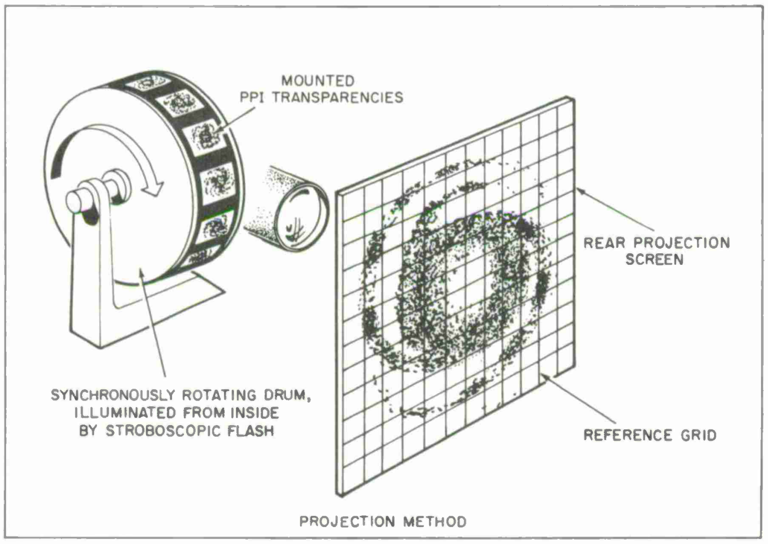


Fig. 14. Change Detection MTI (CDMTI) can be implemented photographically by storing a sequence of display frames on film for projection as a time lapse motion picture, or with a video recorder of the "instant replay" type.

In the case of aircraft systems, we place high priority on significant improvements to existing radars, which we believe can be implemented within a year, and which will enable these radars to measure target velocity.

For the future, the panel has attempted to describe an ensemble of the right instruments to do the job and the airframes necessary to carry them. Even this system has been compromised to reflect the realities of economic life — we have forced our system to fit modified aircraft from our current inventory.

We should ultimately like to see the design of a completely new reconnaissance aircraft, developed and outfitted to do precisely the task at hand — make the right measurements, in the right place, at the right time.

A. Surface-Based Radars

1. Short-Term

Improve our utilization of ground-based coastal radar systems, especially in the critical 12- to 24-hour period prior to hurricane landfall. On the U. S. Weather Bureau radars, implement change detection, moving-target indication, i. e., the Fujita echo displacement velocity measuring technique (see Fig. 14). Implement quantitative reflectivity contour mapping measurements. Standardize and calibrate all radars. Implement reliable communication system to transmit digital, reflectivity, and velocity maps from radars to the NHC on call. Utilize FAA radars on an emergency basis during storm periods. On the FAA radars, implement change detection, moving-target indication. Utilize the Doppler capability of FAA radars to measure radial velocities in hurricane rainbands with appropriate range gates. Provide for the possibility of disabling the circular polarization feature of FAA radars during hurricane situations.

2. Intermediate-Term

Begin immediately the development of an air-transportable, mobile, ground-based radar for the purpose of investigating the feasibility of the various measurement techniques proposed and the advisability of retrofitting these modifications on all coastal and "tornado-alley" WSR-57 radars.

B. Airborne Radars

1. Short-Term

On airborne radars, increase dynamic range and normalize the echo power for range. Add contour mapping. Provide at least three 10-inch or larger displays. Standardize and calibrate all radars. Implement change detection, moving target indication prototype for evaluation, the dual-beam wind measurement technique (Fig. 15) on the APS-20, AVQ-30, and on the APN-59 (3.2-cm radar), the latter needing a modification to permit tilting the antenna downward to at least 45° from the horizon.

2. Intermediate-Term

Combine X-band, height-finding function with research functions. Eliminate an independent vertical-beam Doppler radar, but design the winds-below-aircraft radar to provide this function. The winds-below-aircraft radar can time-share the transmitter/receiver package and data processor with the search radar. No microwave radiometric temperature profiling. Rely on Doppler radar measurements instead.

3. Long-Term

Develop a combined location, navigation, and hazard-avoidance radar and mapping and measurement radar at 9-cm wavelength, with a fully coherent transmitter/receiver chain.

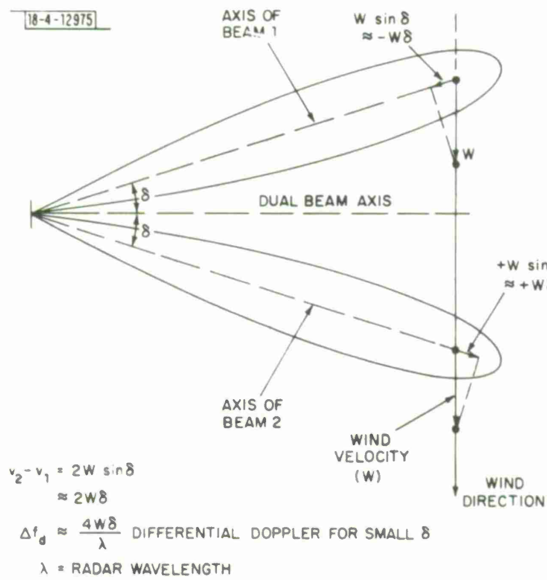


Fig. 15. The Dual Beam MTI (DBMTI) technique. Echoes from the two beams are mixed to produce a difference frequency which represents the differential Doppler frequency produced in the two beams by the moving scatterers. After Atlas and Wexler, J. Appl. Meteorol., October 1965.

Antenna beamwidth should be less than 2°. The antenna must scan at least the entire 180° forward sector. The system should provide general mapping out to 250 n. mi, with display updated at least once a minute. Provide for Doppler velocity measurements. Quantize contour reflectivity and a storage-type display. Provide a vertical mapping radar by adding a 3-cm coaxial horn to the previous system. To permit vertical storm mapping with the same antenna, time-share the antenna to provide the several functions. Develop display and data-processing techniques to measure maximum storm top and bases of at least two echo layers to the left and right of the aircraft track out to 50-n. mi range.

Develop a four-beam radar for measuring winds below or above the aircraft (Fig. 16). Conduct research with this radar to determine the feasibility of measurements of sea-state and surface winds. Provide a fifth beam pointing vertically for measurement of up- and down-drafts, raindrop size distributions, the height of the bright band, echo tops and bases, and a vertical reflectivity profile. Consider use of this radar for altimetry.

Develop a prototype 35- to 60-GHz radiometer for vertical temperature profiling in substantially clear regions, including the hurricane eye. Perform the necessary research and develop tactics to bring to an operational status. Implement a scanning 2- to 8-cm microwave radiometer to spot-map sea-surface temperatures in substantially precipitation-free regions.

C. Auxiliary Subsystems

Implement chaff dispenser to provide auxiliary wind tracers in echo-free regions. Implement Beukers Laboratories' dropsonde system for wind, temperature, humidity, and pressure measurements below aircraft, especially where data from other sensors is lacking. Develop a comprehensive on-board data-processing and recording system for real-time and post-flight displays and analysis. Develop tornado detection Doppler or pseudo-Doppler radars for both ground and airborne use. Real-time velocity, or tornado signatures are required.

D. Additional Subsystems for Research Operations

Implement joint development of airframe and major coherent radar in the 8- to 9-cm wavelength region. Develop Doppler techniques to permit unambiguous range display to 300 n. mi, with simultaneous unambiguous Doppler velocity to $\pm$ 100 meters per second. Develop S-band, side-looking, phased-array Doppler radars for two aircraft to be flown on courses perpendicular to one another, in which radial Doppler velocities are stored in the earth reference frame, with the data from the two aircraft combined by computer into a complete vector velocity field. Develop several two-station, ground-based, S-band Doppler radars for deployment along the most vulnerable coastal positions for use in complete velocity-reflectivity mapping of hurricanes. Design new systems so they may be operated aboard ships.

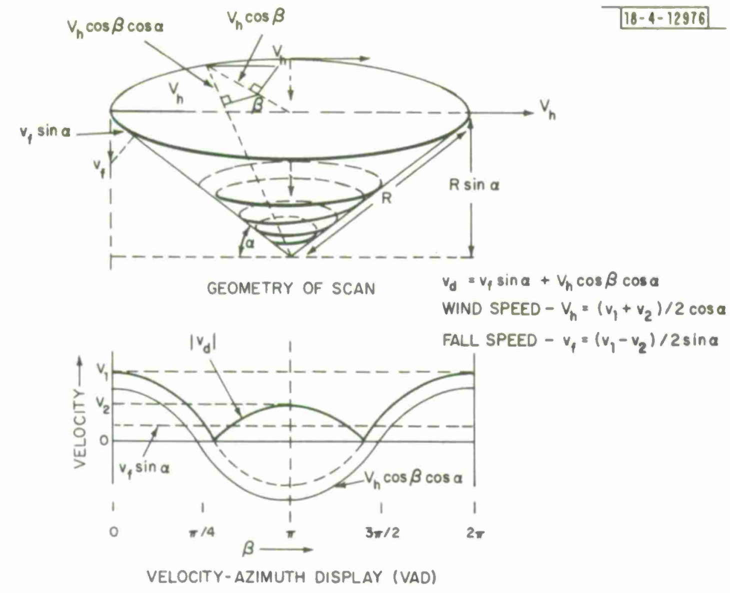
Research and Novel Measurements Panel

Recommendations of this panel are cast in three categories:

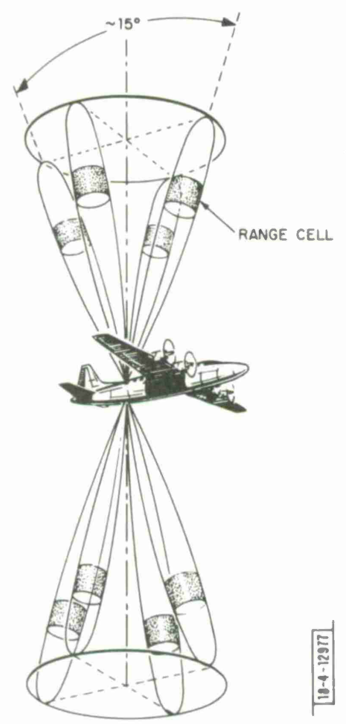
1. Current instruments and techniques used in hurricane reconnaissance; implementation possible in 1970-72 period;

2. Techniques under study (not yet flown in aircraft); implementation by 1975;

3. Techniques requiring further research and study; operational use of successful developments beyond 1975.



(a) VAD. After Atlas, Advances in Geophysics 10, 1964.



(b) WIBAR (Winds Above/Below Aircraft).

Fig. 16. The Velocity Azimuth Display (VAD) technique as used with fixed radars compared with a four-fixed-beam method to be used on aircraft. The latter concept is not unlike a Janus Doppler radar navigator except that the velocity of hydrometeors relative to the aircraft is measured, rather than the velocity of the aircraft relative to the ground.

A. Immediate Implementation

Establish a hurricane reconnaissance central calibration facility. The facility should be co-located with existing laboratory and flight facilities near rawinsonde stations. The Miami Research Flight Facility (RFF) is one such location. The activities of this facility would include ground calibration and evaluation of removable instruments; in-flight calibration by comparison with selected rawinsondes and dropsondes; selection, calibration, and comparison of rawinsondes and dropsondes; six-month calibration cycle for each aircraft; collaboration with aircraft meteorological officer to evolve the most effective data reporting.

The tasks of this facility would include:

1. Development of calibration procedures;
2. Maintenance of suitable standards;
3. Construction, purchase, and operation of calibration equipment;
4. Testing, calibration, and evaluation of all aircraft instruments;
5. Sampling, testing, and standardization of sondes for use in hurricane environments;

The equipment this facility would need is:

1. Controlled altitude chamber for flight pressure and temperature;
2. Subsonic wind tunnel with two-phase water capabilities;
3. Large-area black body for absolute radiation calibration;
4. Controlled humidity changes;
5. Standard laboratory instruments and data recording.

There are systems that need either improved calibration procedures or a better understanding of phenomena related to the measurement technique, or both. Current instruments which fall into this category are:

1. Pressure, humidity, and temperature sensors on dropsondes;
2. Rosemount temperature probe;
3. Vortex thermometer;
4. Dewpointer.

B. Intermediate Implementation

We expect recommended actions in category #2 to take a somewhat longer time to accomplish, not because they are untried, but because they are untried in aircraft. The adaptation of measurements made on the ground to aircraft might well involve unforeseen problems as well as the more obvious ones. For the 1970-75 period; operational use after 1975. We recommend:

1. Investigation of the potential of laser wind velocity measurements in clear air;
2. Radar velocity measurements of condensed phases already discussed;
3. Instrumentation for aircraft for radiometric soundings for temperature measurements and cloud structure determinations;
4. Determination of total water content, using Lyman-α absorption.

It is expected that not all of these techniques will survive for eventual use on operational aircraft, but they offer enough potential to make important measurements to warrant flight testing.

C. Future Implementation

In the third category, we have research programs with unforeseen application dates, characteristic of the more basic or "risk" research.

Satellites do not now provide some of the kinds of data the forecaster uses in his prognoses. We believe it to be of great value to bridge this gap by not only developing improved satellite sensor data, but also developing new forecasting procedures that make more effective use of these data.

We see also a need for increased effort on model building, with emphasis on the application of data taken in the field and of measurements made in the laboratory to these models to improve their validity.

One of a number of examples of a field experiment would be the use of chemical injectants, possibly NO, to map the wind velocity fields in hurricanes. The oxidation of NO in the atmosphere would provide radiation that could be sensed remotely, not requiring physical <u>in situ</u> collection as is the case with SF_6, an injectant previously used in hurricane experiments.

We list other items in this category which we believe deserve further investigation.

1. Simultaneous measurements of the amounts of H_2O in all phases and of particle and drop-size distributions;
2. Spectroscopic temperature soundings;
3. Remote sensing of sea state using radar or laser scattering;
4. Determination of atmospheric component densities using laser-Raman scattering;
5. Total density measurements in the atmosphere from laser-Rayleigh scattering;
6. Aerosol concentration estimates using appropriate difference between laser-Rayleigh and laser-Raman scattering.

The energy of a hurricane is so large that we cannot hope to diminish its strength by matching energies. In fact, seeding experiments involve energy releases that are 10^{-8} to 10^{-9} that of the storm. It is, therefore, of the utmost importance that we modify the storm with full appreciation of its structural integrity and arrange for energy release at such locations as are shown to present optimum stations for reducing maximum wind speeds. However, the reduction of the maximum winds of the storm by even a small amount portends a great reduction in damage suffered. We urge that work on the analysis, understanding, and modification of hurricanes be vigorously pursued and that items of risk research be supported to help us achieve effective modification.

XIII. LATENT IMAGES — IDEAS NEEDING FURTHER DEVELOPMENT

During the course of the Study, a number of ideas came up that on the surface seemed to warrant further investigation. Time did not permit such analysis during the Study. Some are listed here and described briefly.

A. Hurricane and Typhoon Reconnaissance from Instrumentation Ships

It should be possible to get important information on tropical storms through the opportunistic use of some of the sophisticated Doppler radars aboard our instrumentation ships. It was suggested by R. H. Simpson in 1966 that a radar-equipped ship take up a

position in the right rear quadrant of the storm about 100 miles from the eye and maintain this position for continuous surveillance of the radar structure with PPI and RHI radars. The design and operation of a ship for this purpose alone would be costly (it costs about $1 million a year to keep an ocean station vessel on station), but possible use of existing ships should be investigated. Canada now has a weathership, the Vancouver, equipped with a large tracking radar system, operating in North Pacific waters.

B. Hurricane and Typhoon Reconnaissance from Submarines

It appears possible to get a measure of sea-surface conditions from a submerged submarine by observing sub-surface pressure fluctuations or by observing the nature of water noise with underwater sound equipment. One might be able to derive the location of the eye and/or the region of maximum winds from these observations. An acoustic buoy could be released to surface and measure sea-level atmospheric pressure.

C. A Standardized Launcher for Dropsondes and Bathythermographs

The possibility of providing a common launch/calibration chamber for both dropsondes and bathythermographs appears attractive for it will allow all reconnaissance aircraft to use either instrument. The addition of a pressure instrument to the bathythermograph should permit worthwhile surface measurements.

D. Storm Location and Tracking by Analysis of Tide Gauges or Seismographs

Pacific islanders have become quite adept at reading an approaching storm from the swell, and at using wave diffraction patterns around the islands as an aid to navigation. We have developed methods of correlating signals obtained from large arrays of seismic detectors to measure the direction of arrival and other characteristics of seismic waves. It may be possible to use data-processing techniques derived for seismic arrays in connection with data recorded at coastal tide gauges, or with the microseisms generated by wave action to establish the direction and intensity of severe storms at sea.

XV. CONCLUSIONS

In this Study, we have established a number of desirable and, we believe, achievable goals, viz., to reduce hurricane forecasting differentials to less than 50 miles, to improve our forecasting of maximum winds, and to devise a method of modification capable of reducing the maximum winds of a hurricane by 25%. We have listed meteorological observations by priority and have suggested improvements in our methods of making these observations. A surveillance system is blocked out in which airborne reconnaissance plays a major but by no means exclusive role. We have tried to devise a balanced system in which needed observations are made by appropriate instruments mounted on platforms which best suit the purpose. To this end, the system employs not only aircraft, but also satellites, fixed ground stations, air-transportable mobile stations, and ad hoc use of FAA and DoD radars to provide the best possible severe storm surveillance. Direct communications with links of reasonable capacity are paramount, and accurate navigation and location essential. We believe direct and continuous communications between the warning centers and the general public in addition to public officials to be desirable. It must be emphasized that, for lack of time, many of our recommendations are made without detailed consideration of costs and trade-offs among the several iterations possible within the total system structure. In some instances, several approaches could accomplish the same measurement, and the final choice would depend upon other options taken among the system variables. We do believe, however,

that many of these measurements are important and difficult enough to warrant a multi-faceted approach in the research and development stage.

Our storm warning system works surprisingly well in spite of its structure as a rather loose confederation of participants serving many different masters, and deriving funds from different sources. It should work even better if not only a focal point of responsibility for the total task is established, but also this responsibility carries with it control of the funds required to support adequately all the participants in the task.

APPENDIX I

Airborne Severe Storm Surveillance Systems Summer Study

3-28 August 1970

Full-Time Participants

Professor David Atlas
Department of Geophysical Sciences
University of Chicago
5734 South Ellis Avenue
Chicago, Illinois 60637

Dr. Eugene J. Aubert
Center for the Environment & Man
250 Constitution Plaza
Hartford, Connecticut 06103

Dr. Edward M. Brooks
Department of Geology & Geophysics
Boston College
Chestnut Hill, Mass. 02167

Mr. Cornelius J. Callahan
Systems Management Engineer
ESSA Headquarters
6010 Executive Boulevard
Rockville, Maryland 20852

Mr. Eugene S. Cotton
Room B-260
MIT Lincoln Laboratory
Lexington, Mass. 02173

Dr. Seymour Edelberg
Room L-124
MIT Lincoln Laboratory
Lexington, Mass. 02173

Dr. Elmer J. Frey
Measurement Systems Laboratory
Room N51-309
Mass. Institute of Technology
Cambridge, Mass. 02134

Mr. Raymond B. Harlan
Measurement Systems Laboratory
Room N51-309
Mass. Institute of Technology
Cambridge, Mass. 02134

Dr. Melvin A. Herlin, Vice Chairman
Room A-209
MIT Lincoln Laboratory
Lexington, Mass. 02173

Dr. James W. Meyer, Chairman
Room A-127
MIT Lincoln Laboratory
Lexington, Mass. 02173

Dr. Stanford S. Penner
Applied Physics Department
University of Cal. at San Diego
La Jolla, California 92037

Lt. Col. Foster A. Post, USAF
Hq., Air Weather Service (AWOAO)
Scott Air Force Base
Illinois 62225

Mr. Charles M. Rader
Room B-327
MIT Lincoln Laboratory
Lexington, Mass. 02173

Professor Robert W. Simpson
Department of Aeronautics
Mass. Institute of Technology
Cambridge, Mass. 02134

Mr. John Whitman
Missile Systems Division
Raytheon Company
Bedford, Mass. 01730

Major William V. Yelton
9 WRWg(V)
McClellan Air Force Base
California 95652

Mr. John A. Zalovcik
Mail Stop 247
NASA Langley Research Center
Hampton, Virginia 23365

Participants for Two Weeks or More

Mr. Howard Friedman
ESSA Research Flight Facility
P.O. Box 197 IAB
Miami, Florida 33148

Mr. Alan Miller, Project Manager
Experimental Meteorological Laboratory
P.O. Box 8044
Coral Gables, Florida 33124

Professor Ralph Zirkind
Department of Electrical Engineering
University of Rhode Island
Kingston, Rhode Island 02881

Part-Time and Liaison Participants, and Guests

Colonel Thomas A. Aldrich
Vice Commander
Headquarters
Air Weather Service (MAC)
Scott Air Force Base, Ill. 62225

Dr. Pauline M. Austin
Senior Research Associate
Dept. of Meteorology
Mass. Institute of Technology
Cambridge, Mass. 02134

Mr. Alvin D. Bedrosian
Chief, Army Scientific Liaison Office
Mass. Institute of Technology
Cambridge, Mass. 02134

Brig. Gen. W. H. Best, Jr., USAF
Commander
Air Weather Service (MAC)
Scott Air Force Base
Illinois 62225

Mr. John M. Beukers, President
Beukers Laboratories, Inc.
1324 Motor Parkway
Hauppauge, N. Y. 11787

Col. T. L. Bishop
Director, Air Operations
Headquarters, Air Weather Service
Scott Air Force Base, Illinois 62225

Mr. B. Charles
Hughes Aircraft Company
Space Systems Division
P.O. Box 92919
Los Angeles, California 92229

Lt. Col. J. F. Church, CREU
Aerospace Instrumentation Laboratory
AF Cambridge Research Laboratories
L. G. Hanscom Field
Bedford, Mass. 01730

Dr. Robert K. Crane
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. Robert Crudale
the MITRE Corporation
P.O. Box 208
Bedford, Mass. 01730

Dr. R. M. Cunningham, CRHC
Meteorological Laboratory
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Dr. Gerald P. Dinneen, Director
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. Carlos R. Dunn
Chief, Scientific Services
Weather Bureau Eastern Region
585 Stewart Avenue
Garden City, New York 11530

Cdr. Harry J. Englehart
Assistant for Current Operations and
Facilities Management
Naval Weather Service Command
Building 200
Washington Navy Yard
Washington, D. C. 20360

Dr. Robert D. Fletcher
DCS/Aerospace Sciences
Headquarters
Air Weather Service (MAC)
Scott Air Force Base, Ill. 62225

Dr. Sigmund Fritz, Chief Scientist
National Environmental Satellite Center
Washington, D. C.

Dr. R. Cecil Gentry, Director
National Hurricane Research Lab.
P.O. Box 8265, U. of Miami Branch
Coral Gables, Florida 33124

Mr. Samuel O. Grimm, Chief
Emergency Warning Branch
Weather Bureau Headquarters
Gramax Building
Silver Spring, Md. 20910

Dr. K. R. Hardy, CRHA
Meteorological Laboratory
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Dr. A. G. Hill
Vice President for Research
Mass. Institute of Technology
Cambridge, Mass. 02134

Lt. Cdr. F. E. Horn, Jr.
Meteorological Division
Naval Air Systems Command
Washington Navy Yard
Washington, D. C. 20630

Mr. C. V. Horrigan, ESSI
Aerospace Instrumentation Program Office
Electronic Systems Division
L. G. Hanscom Field
Bedford, Mass. 01730

Dr. William Hughes, Dean
Department of Electrical Engineering
Oklahoma State University
Stillwater, Oklahoma 74074

Dr. Kenneth L. Jordan
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. Jack Keating
The MITRE Corporation
P.O. Box 208
Bedford Mass. 01730

Dr. Edwin Kessler, Director
National Severe Storms Lab.
1616 Halley Avenue
Norman, Okla. 73069

Mr. Uve Lammers, CRDT
Microwave Physics Lab.
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Mr. Peter E. Larsen
Naval Air Systems Command
NAIR 5403A, Navy Dept.
Washington, D. C. 20360

Mr. Jean T. Lee
National Severe Storms Lab.
1616 Halley Avenue
Norman, Okla. 73069

Mr. E. Lissey
Hughes Aircraft Company
Space Systems Division
P.O. Box 92919
Los Angeles, Calif. 92229

Cdr. Alvin Marsh
Commanding Officer, Weather Squadron
VW-4, Naval Air Station
Jacksonville, Florida

Mr. W. Mavroides
Microwave Physics Laboratory
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Mr. John H. McClennan, Manager
Boston District Operation, Eastern Region
General Electric Co. Defense Programs
114 Waltham Street
Lexington, Mass. 02173

Mr. Robert Miller
Air Force Global Weather Central
Offutt Air Force Base, Neb. 68113

Lt. Cdr. Peter Morrill
National Data Buoy Development Project
Coast Guard Headquarters
Washington, D. C.

Mr. J. F. Morrissey, CRES
Aerospace Instrumentation Lab.
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Mr. Walter E. Morrow, Jr.
Assistant Director
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. C. E. Muehe
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. R. F. Myers, CRHO
Meteorological Laboratory
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Capt. J. H. Negele, USN
Deputy Commanding Officer
Naval Weather Service Command
Washington Navy Yard
Washington, D. C. 20360

Mr. J. C. Payne, CREB
Aerospace Instrumentation Lab.
AF Cambridge Research Labs.
L. G. Hanscom Field
Bedford, Mass. 01730

Professor Willard Pierson
Dept. of Meteorology
New York University
Washington Square
New York, N. Y. 10003

Mr. Emmett Pybus
Department of Electrical Engineering
Oklahoma State University
Stillwater, Oklahoma 74074

Col. C. E. Roache
ESSA Headquarters
6010 Executive Boulevard
Rockville, Maryland 20852

Dr. Lawrence Roberts, Director
Information Processing Techniques
Advanced Research Projects Agency
Washington, D. C. 20301

Dr. Stig Rossby
National Center for Atmospheric Research
Boulder, Colorado 80302

Dr. John Ruze
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Professor Frederick Sanders
Department of Meteorology
Mass. Institute of Technology
Cambridge, Mass. 02134

Mr. James H. Shanley
Executive Vice President
Beukers Laboratories, Inc.
1324 Motor Parkway
Hauppauge, N. Y. 11787

Dr. Robert Simpson, Director
National Hurricane Center
P.O. Box 8286
Coral Gables, Florida 33124

Lt. Cdr. J. H. Smithey
Naval Air Systems Command HQ
4306 Munitions Building
Washington, D. C.

Major Charles Stephens
Air Force Global Weather Central, MAC
Offutt Air Force Base, Neb. 68113

Mr. G. H. Stocker
Department 72-71
Bldg. 311, Plant B-6
Lockheed-California Company
Burbank, Calif. 91503

Mr. Melvin L. Stone
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. E. F. Thomas, ESSIA
Airborne Instrumentation Engineering Div.
Electronic Systems Command
L. G. Hanscom Field
Bedford, Mass. 01730

Mr. Paul Twitchell
Office of Naval Research
495 Summer Street
Boston, Mass. 02210

Major James T. Zumwalt
Director of Operations
Air Weather Service
Scott Air Force Base, Ill. 62225

Administration

Dr. James W. Meyer, Chairman
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Dr. Melvin A. Herlin, Vice Chairman
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

*Mr. Roy C. Cummings, Administrative Asst.
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mr. Robert V. Driscoll, Administrator
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

*Mr. Ralph W. MacKnight, Tech. Asst.
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

Mrs. Carol A. Mawdsley, Secretary
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

*Mrs. Mary G. Rutledge, Secretary
MIT Lincoln Laboratory
P.O. Box 73
Lexington, Mass. 02173

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* Part-Time

APPENDIX II

Airborne Severe Storm Surveillance Systems Summer Study

Seminar Agenda Theme Speakers

Date	Topic	Speaker
Tuesday, 4 August	Keynote Address	Dr. Roberts, ARPA
	Airborne Weather Reconnaissance by the Air Force	Col. Aldrich, USAF
	Hurricane Reconnaissance Operations by the Navy	Cdr. Marsh, USN
	Air Force Global Weather Central	Maj. Stephens, USAF
	Severe Storm Forecasting and Warning (with Emphasis on Tornado Forecasting)	Mr. R. Miller, AFGWC
	The Air Weather Service as a National Resource	Brig. Gen. Best, AWS
Wednesday, 5 August	Airborne Reconnaissance of Severe Convective Storms (with Remarks on Tornado Forecasting, Detection, and Warning)	Mr. Lee, NSSL
	Weather Surveillance and Reconnaissance from Satellites	Dr. Fritz, NESC
	A Method of Getting Improved Pictures from Weather Satellites	Mr. Myers, AFCRL
	Balloon-Borne Storm Surveillance	Mr. Payne, AFCRL
	Hurricane Modification Potential (with Remarks on Celia and Forecasting and Warning Problems)	Dr. Gentry, NHRL
Thursday, 6 August	Hurricane Research Programs (Including a Discussion of Seeding and Airborne Reconnaissance Requirements for Hurricane Modification Programs)	Dr. Gentry, NHRL
	Some Remarks on the Pragmatic Aspects of Airborne Weather Research Operations	Lt. Col. Church, USAF
	Numerical Models in Hurricane Predictions	Prof. Sanders, MIT
	Air Force Airborne Reconnaissance Improvement Programs	Mr. Thomas, ESD
Friday, 7 August	Navy Airborne Reconnaissance Improvement Programs	Lt.Cdr. Smithey, USN
	Special Weather Reconnaissance Equipment for the Navy's WC-121N Aircraft and the Data Acquisition Logging System (DALS)	Mr. Larsen, NASC
	National Posture in Forecasting and Warning Services	Mr. Grimm, ESSA
	Airborne Reconnaissance of East Coast Winter Storms	Mr. Dunn, ESSA

(Friday, 7 August, cont'd)	Ship and Ocean Buoy Weather Stations	Cdr. Morrill, USCG
	Recent Developments in Airborne Instrumentation	Lt. Col. Church, USAF
	ESSA's Research Flight Facility	Mr. Friedman, RFF
	Some Topics in Weather Radar Research	Dr. Hardy, AFCRL
	Probing the Upper Troposphere with Millimeter-Wave Forward Scatter	Mr. Lammers, AFCRL
	Three-D Radar Weather Profiles with a Line-Feed Antenna	Mr. Mavroides, AFCRL
Monday, 10 August	Weather Reconnaissance Command Control and Communications, Operations Plans and Coordination	Mr. Callahan, ESSA
	Some Topics in Satellite Communications	Dr. Jordan, LL
	Routine Data Collection from Airborne Platforms	Maj. Yelton, USAF
	Some Research Programs at the National Center for Atmospheric Research (NCAR)	Dr. Rossby, NCAR
Tuesday, 11 August	A Discussion of the Relation Between Maximum Winds and Minimum Surface Pressure in a Hurricane	Dr. Fletcher, AWS
	Weather Reconnaissance with Balloon-Borne Radiosondes Using Hyperbolic Navigation Systems — A Discussion of the LOCATE System	Mr. Beukers, Beukers Lab.
	Real-Time Cloud Surveillance for Reconnaissance Mission Planning and Control — A System of Real-Time Video Display	Mr. Charles, Hughes A/C.
	Satellite Observation of Winds and Waves over the Ocean	Prof. Pierson, N.Y.U.
	Radar Scatterometer (RADSCAT) Design and Implementation	Mr. Godbey, G.E.
	A Synagraphic Mapping System Using Digital Computer and Display	Mr. Crudale, MITRE
Wednesday, 12 August	A Theory of Meteorological Measurements from an Aircraft	Mr. A. Miller, ESSA EML
	High-Altitude Platforms for Reconnaissance; The YF-12A, SR-71, and U-2 Aircraft	Mr. Stocker, Lockheed
	Research on Spherics as Indicators of Rain, Hail, and Tornadoes	Prof. Hughes, Okla. State
	Experimental Airborne Spherics Detection Techniques	Dr. Pybus, Okla. State
	Some Comments on the State of the Art in Inertial Navigation	Dr. Frey, MIT

Thursday, 13 August	Radar Measurements of Meteorological Phenomena	Prof. Atlas, U. Chicago
	Radiometric Measurements of Meteorological Phenomena (Visible, Infrared, and Microwave Radiometry; Imaging Systems, Photography, and Active Optical Systems)	Prof. Zirkind, U.R.I.
	The Use of Sulphur Hexofluoride (SF_6) Tracers in Hurricane Investigations	Mr. Friedman, RFF
	Some Comments on the Relationship Between Hurricane Wind Profiles and Property Damage and Loss	Dr. Aubert, U. Conn.
Monday, 17 August	Hurricane Forecasting and Warning at the National Hurricane Center, including a Discussion of Hurricane Celia, the Forecasts, Warnings, and Damage it Caused; A General Description of Hurricane Forecasting Problems; Some Comments on Numerical Forecasting; Some Comments on NHC Programs; and a Discussion of the Kind of Measurements Needed from Airborne Reconnaissance	Dr. Simpson, NHC
Tuesday, 18 August	Roundtable Discussion of Meteorological Instrumentation	Mr. Morrissey, AFCRL
	Digital Signal Processing	Mr. Muehe, LL

APPENDIX III

Airborne Severe Storm Surveillance Systems Summer Study

3-28 August 1970

PANEL ORGANIZATION

* Contemporary Operations	Callahan, Chairman Post Yelton (Friedman)
Meteorology	Brooks, Chairman Aubert (Miller)
Platform	Frey, Chairman Harlan Simpson Zalovcik
Radar and Radiometry	Atlas, Chairman Whitman Rader
Research/Novel Measurement Techniques	Penner, Chairman Cotton Edelberg (Zirkind)

* Upon completion of review report on Contemporary Operations, Callahan and Post joined the Platform Panel and Yelton joined the Meteorology Panel.

APPENDIX IV

STUDY REVIEW AGENDA

28 August 1970

9:30	Introduction and Overview	J. Meyer
	Reports of Panel Chairmen	
10:30	Meteorology	E. Brooks
11:30	Research/Novel Measurements	S. Penner
12:30	Lunch	
1:30	Radar/Radiometry	D. Atlas
2:30	Platform	E. Frey
3:30	Discussion	

Invited Guests

Mr. A. D. Bedrosian, ALO, MIT	Mr. Jack Keating, MITRE
Brig. Gen. W. H. Best, Cdr. AWS	Cdr. A. Marsh, NAS
Col. T. L. Bishop, AWS	Capt. J. H. Negele, NWSC
Dr. A. G. Hill, MIT	Col. C. E. Roache, ESSA
Lt. Cdr. F. E. Horn, NASC	Dr. L. G. Roberts, ARPA
Mr. C. V. Horrigan, ESD	Mr. P. Twitchell, ONR
Mr. W. E. Morrow, Lincoln Lab.	Maj. J. T. Zumwalt, AWS

APPENDIX V

Summer Study Work Statement

AIRBORNE SEVERE STORM SURVEILLANCE SYSTEM

Conducted by
Lincoln Laboratory, Massachusetts Institute of Technology
With the Support of
The Advanced Research Projects Agency

3-28 August 1970

Dr. James W. Meyer, Chairman

PRELIMINARY STATEMENT

This nation needs, in its own defense against the ravages of violent storms, an integrated airborne surveillance system that can detect, track, and analyze weather conditions that are, or can produce, a hazard to life and property. This airborne system must be appropriately coupled into the responsible forecasting and warning centers to enable these centers to accurately predict the course and severity of these storms. The mobility and readiness of the airborne system would make it possible to concentrate significant technological resources in threatened areas as these threats develop unexpectedly or as anticipated during periods of high storm frequency.

The operational system, which has as its principal task the collection of information needed for forecasting and warning, must be so configured that data derived from its missions is calibrated and preprocessed in a form that will make it most useful to research workers. We expect, for example, that the airborne system can contribute to the development of satisfactory methods of modifying severe storms through contributions to our understanding of their genesis and the dynamics of their growth and decay.

As we continue our attempts to provide effective weather modification, especially those efforts to dissipate violent storms harmlessly, proper surveillance and measurements are particularly important in determining the efficacy of our methods. Early experiments on hurricane seeding, for example, have to be carried out well away from land areas, making airborne operations a necessity.

While most of the meteorological data needed for effective long-range, large-scale, numerical forecasting can be obtained on a global scale with a multiple satellite system, mesoscale observations from airborne platforms can provide data for preliminary tests of models, can fill unanticipated hiatuses in satellite surveillance coverage, and can provide special high-resolution measurements in atmospheric volumes of special interest.

Satellites and aircraft can perform complementary functions in severe storm surveillance and warning. Clearly, the aircraft system configuration and its instrumentation must reflect current and anticipated satellite surveillance technology.

Satellite communications appear to offer the capacity, flexibility, and reliability needed in the essential task of getting observations back to the forecasting and warning centers.

The maintenance and operation of an airborne severe storm surveillance system, since defense missions are affected and defense resources absorbed in civilian emergencies, is an appropriate operational task for the Department of Defense. It is essential that civilian agencies charged with responsibilities in environmental defense, such as the Weather Bureau, can rely on the system for needed data and can task the system for special missions. Moreover, it is expected that civilian agencies equipped with flight facilities will continue to emphasize research in their operations and will prefer to leave the more operational missions to elements of the Department of Defense. This posture will likely continue as long as the severe storm surveillance system is responsive to overall national needs.

STUDY OBJECTIVE

As a principal objective, the Study Group will attempt definition of the airborne component of an integrated surveillance system consisting of sensory, data-processing, navigation, and communications equipment capable of detecting, tracking, and measuring for analysis hurricanes/typhoons during genesis and development, and during periods of active weather modification. As a secondary objective, we would delineate those airborne system features that could contribute to our understanding and forecasting of tornadoes, convective thunderstorms, and winter coastal cyclones.

DISCUSSION

It is expected that radar weather sensors and navigation systems will play key roles in the instrumented aircraft. Almost without exception, reports on airborne weather radar instrumentation point to the fact that all these radars are superficial adaptations of equipment designed for a totally different purpose. Weather radar researchers, on the other hand, point to the advantages to be gained with a system specifically designed for weather diagnostics. The radars in the severe storm surveillance aircraft must have the advantages of being designed at the outset for their purpose. Radar altimetry in severe storms over the ocean offers special challenges, but also special opportunities for measuring sea state in terms of amplitude and wave number when functioning as a scatterometer. Surface profiles can be recorded.

The navigation system must function well in very bad weather – severe turbulence and atmospherics. The short-wavelength Doppler navigator, for example, which is so effective in measuring true ground speed under ordinary circumstances can be useless in heavy blowing rain.

Timely communication of essential information to the warning centers makes all weather operation of the communications system imperative. Ground terminals to be used with the system will also have to receive consideration in this context.

Particular attention must be paid to the kind of data needed from the system, to the choice of the method of getting it where there are competing possibilities, and to the ordering of priorities for the several kinds of data. The balance between real-time data needs, on-board preprocessing, recording for post-mission analysis, and communications channel capacity must be carefully weighed.

It is of particular importance that elements of an airborne system be developed from the vantage point that suggested airborne observations are unique and have a complementary place among the variety of ways we have of making needed observations of our environment. Study members will have to remain alert to other ways of getting needed information.

STUDY OUTLINE

I. DEFINITION OF SCOPE

A. Review airborne weather observations as now conducted
   1. Routine operations
   2. Research flights

B. Review existing airborne weather instrumentation
   1. Routine operations
   2. Research instrumentation

C. Review satellite surveillance role

D. Identify data needed now and project for the future
   1. Emphasize severe storm surveillance
      a. Hurricanes
      b. Tornadoes
      c. Severe convective thunderstorms
      d. East Coast winter storms

E. Review operational concepts and problems
   1. Unique capabilities of airborne system

F. Identify areas needing technical development or research
   1. Identify areas potentially dangerous

G. Define advanced airborne weather surveillance system

H. Project role of airborne surveillance in weather modification

II. APPROACH

A. Broadly-based, interdisciplinary study group membership Representing:
   1. Meteorology, numerical forecasting
   2. Airborne weather instrumentation
   3. Airborne radar and weather radar
   4. Data processing and display
   5. Communications
   6. Navigation
   7. Optics and Infrared measurements
   8. Airframes and airborne systems

B. Group Orientation Briefings
   1. Review of past performance in severe storms
   2. State of the art — current operational techniques
   3. Recent developments in weather instrumentation
   4. Forecasting techniques and data required
   5. Weather radar in research and observation
   6. Satellites in weather reconnaissance
   7. Radiometric techniques in weather observations
   8. Desirable aircraft characteristics for general weather and severe storm surveillance

II (Continued)

C. Definition of Problem Areas

1. Review alternatives; select approaches

D. Selective System Definition

1. System and subsystem analysis
2. System integration

E. Internal and External Reports

1. Study status reviews
2. Draft report material
3. Prepare oral summary
4. Prepare final written report

III. GROUP MANNING (15-20 PEOPLE)

A. Chairman; Vice Chairman; Administration

B. Areas

1. Meteorology
2. Operations
3. Instrumentation
    a. Meteorological
    b. Radar
    c. Optics and infrared
4. Data recording
5. Data processing and display
6. Communications
7. Navigation
8. Air frames

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None	Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

The report of the Summer Study is presented in two volumes. Volume I, Summary and Recommendations, includes background material, the principal findings supported in most instances by brief discussion, and recommendations, in the form of brief statements, made as a result of the findings. Volume II, Reports of the Working Panels, contains material prepared by the Panels, which represents more detailed discussions in support of both the findings and recommendations.

Airborne reconnaissance required to improve the forecasting and warning of severe tropical storms (hurricanes and typhoons), and to support efforts to achieve effective storm modification, is emphasized. Other methods of getting the necessary information and data are considered, and where appropriate, are recommended as part of the total system. Also discussed is the application of advanced groundbased and aerospace techniques to other kinds of violent weather, e.g., East Coast winter storms and violent thunderstorms producing tornadoes. While it is recognized that a degree of specialization is required for the most effective application of technology to problems, the severe storm surveillance system as a whole is viewed as an important national resource that can be used effectively in our defense against a variety of environmental hazards.

14. KEY WORDS

severe storms	summer study	radar meteorology surveillance systems
winter storms	hurricanes/typhoons	weather reconnaissance
tropical storms	thunderstorms/tornadoes	remote sensing atmosphere
meteorology	airborne reconnaissance/surveillance	

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